1985

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Iowa State University

PH.D. 1985

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International 300 N. Zeeb Road, Ann Arbor, MI 48106

Concentrations of N, P, and K in the corn leaf as affected by weather indexes and selected soil and management factors

by

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A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Department: Agronomy
Major: Soil Fertility

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1985

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INTRODUCTION

Plant analysis has been used to assess the nutritional status of crops in order to determine their fertilizer requirements for maximum yield or economic optimum yield. Its diagnostic capability relies on the premise that nutrient supply, nutrient concentration, and yield are closely related, hence implying that there is a nutrient concentration, the critical concentration, that can be associated with maximum yield or a given level of it. However, it is well documented that the nutrient concentration varies along with the variability of other factors and that, although assumed to be constant, the critical concentration also may vary as those factors vary.

A functional relationship proposed by Ulrich (1943) defines that the nutrient concentration is an integrated value of all the factors that have interacted to affect it, namely, soil, climate, plant, management, time, and other factors. This concept directly suggests that, if plant analysis is to be used as a diagnostic tool, an evaluation of the relationships between the nutrient concentration and these factors must be obtained. Otherwise, the interpretation of the plant analysis results is meaningless if those relationships remain uncharacterized.

It is well known that weather and weather-affected factors can exert a differential effect on plant responses depending on the stage of the crop development at which they occur and that their spatial and yearly variability is also related to the variability in plant responses. Because the effects of weather factors are intimately related with soil characteristics, moisture balance models have been developed to integrate these effects on plant responses through the computation of excess moisture and moisture stress indexes.

Research conducted in Iowa has shown that excess moisture conditions early in the season and moisture stress occurring just prior to and following the silking stage are significantly related with corn yield reductions. Concerning plant analysis, Voss (1962) reported that moisture stress in different periods affected differentially the corn leaf N, P, and K concentrations and modified the effects of applied N and P fertilizers on their respective leaf concentrations. Voss (1969) and Miranda (1981) reported similar results, although they used different moisture stress indexes. However, an evaluation of the effects on the leaf nutrient concentrations of soil moisture conditions (excess moisture and moisture stress) throughout the growing season as well as of their variability in time and space together with soil and management factors has not been performed.

Data on the concentrations of N, P, and K in the corn leaf at silking time and several soil, climatic, management, and location variables were collected in Iowa from 1961 to 1970 in 15 counties representing the major soil areas in the state.

The present research project was undertaken to study the effects on the concentration of N, P, and K in the corn leaf of a number of weather indexes computed for various periods of the growing season along with selected soil and management factors. Multiple regression analysis was used to develop a final prediction model for each leaf nutrient using the statewide data that included 1927 site-year observations. A new variable to account for the effect of the difference of the time of sampling with respect to the silking date was added to the original data set.

The objectives of this research were:

1. To determine the correlations between a number of weather indexes computed for various periods of the growing season and between them and the leaf N, P, and K concentrations;
2. To test and select in a series of quadratic models the most significant soil and management factors for each of the leaf N, P, and K concentrations;
3. To test and select weather indexes computed for various periods of the growing season in the presence of quadratic functions of selected soil and management factors for each of the leaf N, P, and K concentrations;
4. To use and evaluate a summation technique to relate weather indexes computed for continuous subdivisions of the growing season in the presence of quadratic functions of selected soil and management variables for each of the leaf N, P, and K concentrations; and
5. To test and select the most significant interactions between weather indexes and selected soil and management variables and to select a final multiple regression model for predicting each of the leaf N, P, and K concentrations.

LITERATURE REVIEW

Plant analysis has been used to determine the nutritional status of crops and, hence, their fertilizer requirements. The principles supporting this method for such a purpose have been presented and discussed in several reviews (Goodall and Gregory, 1947; Lundegardh, 1951; Ulrich, 1943, 1952; Smith, 1962; Greer, 1970; Bates, 1971; Munson and Nelson, 1973; Kamprath and Watson, 1980); that of Goodall and Gregory was the most detailed and critical of all. Dissertations by Dumenil (1958) and Galmarini (1970) also presented comprehensive literature reviews about the subject. The purpose of the present literature review is to present only those findings pertaining to the factors affecting the plant nutrient concentrations with emphasis on the corn crop.

Plant responses such as yield, growth, or nutrient composition are the result of complex relationships among many factors. Jenny (1941) proposed a general functional relationship which stated that the yield of a crop was a function of soil, climate, time, plant, management, and other factors. Likewise, Ulrich (1943) suggested that the nutrient composition of a plant can be explained by a similar relationship. One of the main criticisms of plant analysis as a diagnostic tool is that it varies along with the variability of many factors, thus preventing an accurate interpretation of the analytical results. Some researchers were disappointed with this method as they realized the complexity of the interactions taking place. Hall (1905) recognized that, if through numerous chemical analyses the "normal nutrient content" of the plant can be established, any deviation from the normal can be used as a guide to the fertilization of a crop. He found that, although the concentrations of P and K in the ash of the plants studied were dependent on the amounts of those elements in the soil, the variations due to seasonal changes or differences in supply of nonessential ash constituents were as great as that from the fertilization. Similarly, Steenbjerg and Jakobsen (1963) reported that the interactions among nutrients made interpretation of plant analysis very difficult and it was virtually impossible to perform a correct interpretation.

Conversely, Ulrich (1943) pointed out that the plant sensitivity to environmental changes is what enables plant analysis to be a diagnostic tool. Goodall and Gregory (1947) realized that environmental effects on plant composition may reduce the diagnostic value of plant analysis if it is required to provide an indication of permanent soil characteristics. If the purpose is to obtain an index of the plant nutrient status rather than the soil nutrient status, then they believed that the diagnostic capability of plant analysis is not affected provided the relation between the yield increase as a result of fertilizer treatment remains unaffected by the environmental conditions.

Macy (1936) observed that, although ordinary growth factors may cause a variation in the percentage content of a nutrient in the plant, the critical percentage is an "ideal" but inherent characteristic which, along with the minimum percentage, varies only under special conditions, such as the P fixation by ammonium within the plant. He stated that when other factors affect the percentage content of a nutrient, they also affect the sufficiency of that nutrient as measured by the response to it, but the percentage content of that nutrient which the plant needs is not changed.

At this point, there seems to be a degree of contradiction in the preceding statements; however, such different conclusions can be associated with the experimental approach followed to draw them. The concept of critical percentage such as that of Macy (1936) or Ulrich (1952) was determined and defined by carrying out experiments in which only one nutrient was varied at a time, with all other factors held at constant, optimum levels. Ulrich (1952) even suggested that the critical percentage is best estimated through the use of solution cultures and, to a lesser extent, by soil cultures and field experiments. Goodall and Gregory (1947) reported that, over a wide range of nutrient factors, the concentration of one nutrient alone was unlikely to be related to the yield over the whole range; they recognized that, in fact, this situation prevails under field conditions. However, if the ideal critical percentage, as defined by Macy to be constant, is determined under field conditions, then the nutrient concentration and the critical percentage are going to vary as a result of the many factors interacting and affecting it.

If a critical percentage or the relationship between yield and concentration is to be used to diagnose fertilizer requirements, the effects of other factors on the relationship has to be assessed. Goodall and Gregory (1947) suggested that the effect of two or more nutrients can be evaluated algebraically by means of regression equations. Lundegardh (1951) included an "interference factor" in the equation to account for the effects of another nutrient and extended his equation to account for the effects of additional nutrients.

Recently, Escano et al. (1981) observed that the optimum nutrient concentration should be determined for relatively uniform sets of soils and that varietal differences also have to be ascertained. In contrast, Sumner (1977a) concluded that the effects of many factors must be studied and calibrated to understand how plant composition varies under different field conditions in order to define the relationships between plant composition and yield.

Several researchers have used regression analysis to relate yield, nutrient concentrations, and other factors. Bennett et al. (1953) determined the regression equation of yield on leaf N and P for eight N-rates experiments on corn. The equation showed a definite relationship between yield and the nutrient concentrations of N and P either when estimated from individual experiments or from the pooled data. Viets et al. (1954) pointed out that, in using multiple regression to relate yield to leaf N and P in corn, the yield was highly correlated with the N and P percentages in the leaf.

Later, other researchers included some other factors in their regressions of yield on nutrient concentration. Dumenil (1958) found an $R^2 = 0.57$ when he regressed corn yields on leaf N, leaf P, and stand level using data from 93 fertilizer experiments conducted on various Iowa soil types over several years.

Voss et al. (1970) applied regression analysis to relate yield to N, P, and K leaf concentrations and other factors. They found that the regression of yield on the leaf concentration of the three nutrients gave an R^2 of only 0.24 but, if the equation included the interaction between leaf N and leaf P, several environmental factors, and the interactions between leaf and environmental factors, the R^2 was 0.74. They concluded that interpretation of plant analysis should include consideration of soil, management, and climatic factors.

Likewise, Swanson et al. (1970) related corn yields to leaf levels of ten elements by fitting different regression models. They reported that, in terms of R^2-values, the square root transformation of the quadratic polynomial ($R^2 = 0.82$) gave the best fit of all the models tested. Peck et al. (1969) also reported a similar R^2-value (0.81) for the regression of corn yields on the leaf levels of ten elements.

From these reports, it can be inferred that, as long as the factors on the right side of the equations proposed by Jenny (1941) and Ulrich (1952) remain relatively constant, the relationship is very close, but as more variability is included along the time and space dimensions, the closeness of the relationship decreases if the sources of the variability remain unidentified.

In most studies of this kind, such regression equations are season or site specific, and their results can be applied only to the same restricted conditions and have a limited extrapolation ability to unknown situations (Sumner, 1977a). For the case of annual crops, the results of plant analysis often are used to estimate the fertilizer needs of the subsequent crop. Hence, this usage implies that, in order to use plant analysis as a diagnostic tool, the complexity imposed by the natural variability of the production factors and their effects on plant responses have to be understood.

Factors Affecting Nutrient Concentrations in the Corn Leaf

Plant parts and time of sampling

Plant factors affecting nutrient concentration are age of the plant or stage of development, physiological age of the tissue, and part of the plant (Goodall and Gregory, 1947; Ulrich, 1943; Lundegardh, 1951; Bates, 1971; Munson and Nelson, 1973). Smith (1962) also included fruiting and translocation effects and added that, "Next to the supply of elements, the physiological age of the tissue is probably the most important factor affecting the nutrient composition of a given species." Lundegardh (1951) recommended that leaf analysis should be on leaves of a definite stage of development at a definite period of development of the plant, preferably shortly before the close of the vegetative growth. He concluded that analyzing the whole plant may be undesirable because minerals in inactive tissues may mask functional differences. He found a definite relationship between the internal nutrient concentration and the vegetative growth.

Bates (1971) concluded in his review that leaves are usually the most satisfactory plant part, although in certain crops, tissues other than leaves are occasionally used. Also, the tissue to be chosen should be the one that gives the best relationship between nutrient concentration and yield. Smith (1962) cited that Lagatu and Maume (1934) considered the leaf as the ideal part since it is the chemical laboratory of the plant. Ulrich and Hills (1967) chose tissues and nutrient fractions which resulted in a sharp transition zone in the calibration curve and which also are relatively easy to sample.

For corn, Tyner and Webb (1946) decided to sample the leaf because "it represents a seat of a very active synthesis." The sixth leaf from the base was sampled because it was easy to recognize and samples were collected at four dates around silking time. They found that leaf N and leaf P decreased almost linearly with time whereas leaf K was about the same in the first and last samplings but was at maximum and the same at the second and third samplings. Later, Tyner (1947) reported a high correlation between yield and leaf levels of N, P, and K in the sixth corn leaf sampled at full silk.

Viets et al. (1954) assessed the relationship between corn leaf concentration of N, P, Ca, Mg, K, and Mn and yield. They sampled leaves at several stages but the second leaf below the ear collected at silking was used more often. They found that correlations between yield and leaf N of leaves were less if sampled prior to silking than at silking. Yields were highly correlated with both leaf N and P of leaves sampled at silking.

Hanway (1962a) studied the relationship between leaf weight and grain yield and concluded that grain yield is a function of leaf area which is a function of the nutrient status as reflected in the chemical composition of the leaves. He remarked that the chemical composition of leaves at silking time can indicate nutrient deficiencies that may reduce leaf area and, subsequently, yield. In other work, Hanway (1962c) assessed the percentages of N, P, and K in different plant parts in relation to the stage of growth. From his results, he concluded that nutrient deficiencies resulted in greater differences in percentages of total N, P, and K in the corn leaves and leaf sheaths than in any other plant part. These differences were at maximum near silking; changes with time and with position on the plant at that time were small. Hence, the time of sampling and the position of the leaves on the plant near silking appeared to be less critical if total N, P, and K are used to diagnose the nutritional status of the plant.

Boswell and Parks (1957) studied the effects of soil K levels on corn yield, lodging, and mineral composition of leaf samples collected periodically through the growing season. They found that the highest concentration of leaf K occurred at the first sampling date (28 days after planting) and that it decreased as the season progressed, although it tended to level off from the second to the third sampling dates (53 and 76 days after planting, respectively). They explained that this decrease was due to a "dilution effect", because prior to the third sampling, the ears were being formed and K was probably being translocated from the lower leaves to the meristematic regions where it was re-utilized in carbohydrate synthesis.

In reviewing the effect of sampling upon nutrient concentration in the corn leaf, Dumenil (1958) concluded that leaf N tended to decrease with time during the time around tasseling and silking but the rate of decrease was affected by the available soil N. The K percentage usually decreased with time through this period but there were some exceptions. With regard to leaf P, there was no definite pattern; however, because leaf N and leaf P are usually positively correlated, the leaf P might be expected to decrease as leaf N does.

Terman and Noggle (1973) studied the nutrient concentration changes in corn as affected by dry matter accumulation with age and the response to applied nutrients. Their findings showed that, at each rate of applied N, the concentrations of N in leaves, ears, and entire tops decreased with maturity while concentrations of P remained about the same. Both Ca and Mg first decreased and then increased with maturity, whereas the opposite trends occurred for K concentrations, showing the reciprocal relationship between K and Ca + Mg in plants. These researchers reasoned that these effects are caused by dilution and/or translocation of a nutrient in the plant tissue with increasing yield and age of the plant. Differences occurred because of varying amounts of variable nutrients, plant population, drought, or growth limiting factors that limited yield potential.

Sumner (1977b) applied a method for interpreting corn leaf analysis which is based on the balance principle and which was originally proposed by Beaufils (1971). He studied the effect of the leaf sampled on the leaf levels of N, P, K, Ca, and Mg. The results showed that the concentrations of the different nutrients varied with the position of the leaf sampled at tasseling and within the sampled leaf. The method was able to make consistent diagnoses of the order of requirement for these elements, irrespective of the position of the leaf on the plant and the portion of the leaf sampled within certain limits.

Other researchers related nutrient content (total amount of a nutrient) of the corn plant to grain yield. Jones (1970) suggested that determinations of the total nutrient contents of plants would minimize dilution effects in interpreting plant analysis data. Walker and Peck (1974) applied regression analysis to study the relationships between yield and nutrient content at three stages of growth in corn. They observed that, in terms of R^2-values, more precise yield predictions could be made from the nutrient contents at early growth stages than from nutrient concentrations. However, nutrient contents were no better than nutrient concentrations in different plant parts at the early and late tasseling stages.

Jones (1963) stated, however, that early sampling is only recommended if a deficiency is thought to be present or developing. Interpretative data for such samples are not usually available and interpretation is difficult because the nutrient composition in the plant changes rapidly in the early vegetative stage.

Varieties

An important question in plant analysis is whether different cultivars of a single species vary in nutrient composition and, thereby, in the potential response to applied fertilizers. Goodall and Gregory (1947) considered that varietal differences in composition reflected the differing ability of the cultivars to absorb nutrients from the soil but not a differing reaction to a given nutrient concentration. If this is the case, standard values can be applied regardless of varietal effects.

Dumenil and Hanway (1965) reported that corn hybrids, especially single-crosses, showed significant differences in leaf N, P, and K which were related to inbred lines. However, they did not know if the differences observed were due to a differing ability to absorb nutrients, to differences in yield responses to applied fertilizers at the same leaf levels, or to differences in critical nutrient levels. They observed that double-crosses are less likely to deviate from the mean than single-crosses or inbred lines; this poses an interpretation problem now since single-crosses are being used widely. Melsted et al. (1969) reached the same conclusion but added that some inbred lines and single-cross hybrids may vary in their critical concentration and especially in the luxury consumption range.

Gorsline et al. (1964) found differences in the type of gene action for nine elements and identified significant interactions with location on the heritability of the concentration of those nutrients in the ear leaf. Rivard and Bandel (1974) reported that, although varietal differences in the concentrations of N, P, K, and Ca in field corn were statistically significant, those differences were not large enough to interfere with interpretation of plant analysis results.

Powell (1968) reported differential leaf composition for N, P, and K among corn hybrids differing in parentage. Holmes (1956), who analyzed the leaf composition of several single-cross hybrids grown under various levels of N fertilizer and plant density, found differences in yields and in the leaf levels of N, P, and K among hybrids. Because composition of the hybrids varied between years, a hybrid x season interaction was suggested. A significant hybrid x N interaction on leaf N, P, and K was also found.

Baker et al. (1966), from analyses of more than 50,000 leaf samples, reported that nutrient composition of corn hybrids differed greatly which indicated that the level of accumulation of elements in the ear leaf was under partial genetic control. In evaluating the P concentration of six corn hybrids, they found that they accumulated leaf P at different rates and the responses of leaf P to applied P were also different among hybrids. Not all hybrids required the same rate of applied P to attain maximum yields. They concluded that the accumulation characteristics of the different hybrids should be known in order to evaluate their nutritional status.

Plant breeders usually perform genetic selection under high and constant levels of applied fertilizers in order to reduce variability; therefore, any differences among genotypes in the uptake and utilization of nutrients tend to be masked. Recently, Kamprath et al. (1982) assessed the uptake and utilization efficiencies of two improved corn populations and an unimproved one. Their results showed that the improved populations produced more total dry matter and grain at each level of N than the unimproved population; increased yield was associated with more ears per plant as N rate increased. The N concentration of whole plants of the improved population at silking was correlated with number of ears per plant which reflected a higher N use efficiency (grain/N rate). The improved population also had a higher N uptake efficiency than the original one.

These workers concluded that the greater N-use efficiency of the improved populations appeared to be related to the genetic potential to develop two ears. This was influenced by the relative time of emergence of the silks from the top and second ear shoots which, in turn, was affected by the N concentration in the plant prior to flowering. Increased N concentration may cause the silks of the second ear to emerge within 24 hours of those of the top ear, thus favoring the development of the second ear. The improved populations attained equal maximum yields but one did so at a lower N rate.

Soil fertility factors and applied fertilizers

The diagnostic capability of plant analysis depends on the assumed principle that the plant reflects the truly available nutrients, regardless of the soil type, thus indicating its own nutritional status and, indirectly, the soil fertility condition (Kamprath and Watson, 1980). This relationship has been observed particularly when just one nutrient was varied at a time under conditions in which all other nutrients and factors were kept at constant and adequate levels for plant growth. However, this relationship is not so clear when other factors are varied.

Kamprath and Watson (1980) pointed out that the P concentration is a quotient (weight of P/weight of dry matter); thus, anything that can cause either the numerator or the denominator to change in a nonparallel manner will either decrease or increase this quotient. They proposed that P in the plant tissue can be expressed by the function:

% P = (P supply, P absorption rate, P translocation rate, P retranslocation rate, rate of P interaction with other nutrients, plant growth rate).

Goodall and Gregory (1947) also considered that the concentration of a nutrient depends on the specific relation of the nutrient to the growth process, the rate of uptake, and the rate of utilization. If N is deficient, no meristems are formed and growth is reduced but the uptake of of P and K continues, reaching a relative high concentration in the plant tissues. They added that the same is true to a less extent with P deficiency, while with a K deficiency, growth does not cease and the N concentration does not rise to the same degree. They stressed that the relative concentration of the nutrient elements in the tissues is not a measure of the level of supply of any particular element but is a function of the total supply of all the elements according to their particular importance in the metabolic processes.

The idea of nutrient balance has also been proposed by some researchers. Shear et al. (1946) stated that, at any level of nutritional intensity, there exists a nutritional balance at which optimum growth for that intensity level will occur. Maximum growth and yield occur only when the proper balance of nutrient elements coincides with the optimum intensity. Dumenil (1961) reported that the N-P balance in the corn leaf appeared to be critical at or near the maximum yield. It has a less critical effect as yield levels decrease because similar yields may occur at different levels in the leaf. Recently, Beaufils (1971) and Sumner (1977a) have proposed a diagnostic method based on the nutritional balance concept.

Conversely, Smith (1962) stated that no one has shown that maximum growth and yield occur upon the coincidence of a specific intensity of each element within the plant even if all environmental factors are simultaneously controlled. He suggested that rather wide ranges of intensity of all elements can occur in many possible combinations without altering plant behavior. However, Bates (1971), by reviewing the evidence presented by some workers (Dumenil, 1961; Ulrich and Hills, 1967; Bould, 1964), supported the idea that the nutritional balance becomes more critical as the optimum yield is approached.

In a series of nutrient uptake experiments with cereals, Lundegardh (1951) reported that the mutual influence of ions (ion interference or ion antagonism), not only in relation to their uptake by roots but also to their distribution in the plant, is so widespread that a generalization of the proportionality between fertilizer application and nutrient uptake is completely unjustified.

The importance of nutrient interactions in regard to plant analysis was also reviewed by Emmert (1961). He defined a nutrient interaction as the enhancing or depressing influence of one ion in a tissue on the concentration of other ions of dissimilar species in that tissue. A shift in content of one ion invariably is accompanied by secondary changes in tissue content of the other ion, although the availability to the plant of the ions interacted upon remains unchanged. In this manner, a response of a tissue to changes in nutrient environment may consist of two distinct events: (1) a primary change based wholly on supply and involving in a direct fashion the element altered in the medium, and (2) an interaction of the primary change on other nutrients in the tissue leading to alteration in content of such nutrients. Recognizing the importance of nutrient interactions on the plant nutrient concentration, Goodall and Gregory (1947), Dumenil (1961), and Munson and Nelson (1973) recommended that the multi-element effects on nutrient concentration and its relation to yield can be assessed by means of multiple regression analysis.

Summarizing the leaf nutrient interrelationships commonly observed in corn, Dumenil and Hanway (1965) pointed out that N fertilization (1) usually increases leaf N but has little effect if leaf P is very low, (2) may increase, decrease, or have no effect on leaf P depending on the relative levels of each nutrient in the leaf, availability of both N and P in the soil, and rates of N and P fertilization, and (3) usually decreases or has no effect on leaf K.

They also reported that P fertilization (1) usually increases leaf P (markedly if K is deficient) but has little effect if N is deficient, (2) usually decreases leaf N, and (3) usually decreases leaf K unless soil K is highly available.

They further explained that leaf N and leaf P are positively correlated over the entire range but can vary independently within a narrow range. If leaf N is low, leaf P will be low; if leaf N is high, leaf P will be medium to high but not low. If leaf N is low and leaf P is slightly higher, it is not known if leaf P is low because of its relationship to leaf N or because available soil P is low. Finally, they reported that K fertilization usually increases leaf K and decreases or has little effect on both leaf N and leaf P.

Voss (1962) used multiple regression analysis to assess the effects of applied N, P, and K as well as other soil and weather factors on the leaf levels of N, P, and K. He found that the change in leaf N due to applied N was affected by soil N, soil K, and stress days in Period 2. Leaf N increased with rate of applied N but the response to applied N decreased as soil N increased; hence, soil N substituted for applied N. The effect of low soil K on leaf N response to applied N was to decrease the effect of applied N; hence, low levels of soil K may have been a limiting factor at some experimental sites. The change in leaf N due to applied P was affected by soil N and stress days in Period 2. The initial effect of applied P on leaf N was negative but less important as soil N increased. The general effect of high levels of soil factors was to increase leaf N. The regression of leaf N on 25 variates gave an $R^2 = 0.65$.

On the other hand, the regression of leaf P on 33 variates gave an $R^2 = 0.64$ and revealed that the change in leaf P due to applied N was affected by stand density and time of planting. As stand increased, leaf P increased due to applied N. The change in leaf P due to applied P was affected by soil P and time of planting. As with leaf N, the soil P substituted for applied P. The effect of applied K was to decrease leaf P but this effect was dependent on the interactions of applied K with applied N and P and the type of hybrid. In general, high levels of soil factors increased leaf P.

Leaf K was also regressed on variates of the same factors. The final regression had 24 variates and gave an $R^2 = 0.69$. The change in leaf K due to applied P was affected by soil K and pH. As soil pH increased from 6.1 to 8.1, the effect of applied P was to decrease leaf K, perhaps due to the effect of pH on soil P availability. The effect of applied K was to increase leaf K. The change of leaf K due to applied N was affected by soil P. As soil P increased, the decrease in leaf K due to applied N decreased. This relationship was also affected by the interactions of applied P and K and the effect of pH on the NK interaction.

Thompson (1962) applied different levels of N and K fertilizer to corn and found that increased K supply increased leaf K, reduced the levels of Mg, Mn, and Al and had little effect on leaf levels of P, B, and Cu. Leaf Ca and Zn increased with the K level up to 30 pounds/acre but were reduced by larger K applications. Nitrogen fertilization usually raised the levels of Mg, Ca, Zn, Cu, and Mn but decreased those of K and Al.

Peck et al. (1969) ascertained the effects of not only the applied rates of N, P, and K fertilizers on corn yields but also the effects of seven additional leaf nutrients on corn yields by means of multiple regression analysis. They found that the levels of applied variables affected the composition of the leaf. They also found a significant association between corn yields and the leaf levels of various nutrients. The significant interactions among leaf nutrients indicated that the critical level of any particular nutrient varied along with leaf levels of other nutrients.

Walker et al. (1971) also used regression analysis to study the effects of 10 leaf nutrients on corn yields, which were stratified into high and low yield classes. They found that leaf nutrient interactions on yield were observed as frequently in the high yield category as in the low one. However, the frequent interactions with Ca in the high level category suggested the need to study the factors affecting leaf Ca.

Voss (1969) regressed the concentrations of N, P, and K in the corn leaf on factors of applied fertility, indigenous fertility, management, and climate in fertilizer experiments on the Monona and Marshall soils of western Iowa. The regression equations of leaf N, P, and K on variates of these factors gave R^2-values of 0.60, 0.47, and 0.66, respectively. The leaf N equation showed that fertilizer N increased leaf N at a linear rate, fertilizer P decreased leaf N at a decreasing rate, and fertilizer K decreased leaf N, but not significantly. Increased leaf N was associated with increased soil pH. At low soil N, all levels of fertilizer N increased leaf N; at the higher soil N, leaf N increased with applied N up to 140 lb/acre and then decreased at a higher N fertilizer level. Leaf N decreased as number of years from meadow increased. The effect of fertilizer N on leaf N was affected by interactions with past cropping, soil N, subsoil N, soil moisture, stand level, and soil yield potential.

Increasing levels of fertilizer N, fertilizer P, soil P, soil K, soil pH, soil yield potential, and soil moisture increased leaf P. Conversely, leaf P decreased with soil N and number of years from meadow. Leaf K was increased by increasing fertilizer N, fertilizer P, fertilizer K, soil K, soil pH, soil yield potential, and plant population. It was decreased by increasing number of years from meadow, weeds, and soil moisture. Fertilizer K had a decreasing marginal effect on leaf K; the negative N x K interaction on leaf K showed that K fertilizer had less effect at higher rates of N. A K fertilizer x soil N interaction also occurred.

The levels of fertilizers applied to corn have increased in recent years to attain higher yields with the new high-yielding varieties. Powell (1968) evaluated the effects of high rates of N, P, and K fertilizers on the chemical composition and yield of corn. The results indicated that leaf N was primarily a function of applied N with some negative effects of applied P and K. The increase in leaf N due to applied N occurred at a diminishing rate. Leaf P was primarily affected by applied P and N, but applied K had a negative effect on leaf P. Leaf K was mostly affected by applied K. Leaf levels continued to increase with added fertilizer as yields leveled off or actually declined.

Galmarini (1970) studied the effects of N, P, and K fertilizer applications on their leaf concentrations and the relationship between leaf percentages and corn yields, using data from 22 experiments carried out in Iowa. He reported that, in general, N fertilizer increased leaf N. Leaf P was increased by P fertilizer and applied N had a highly significant, positive effect on leaf P. Fertilization had little effect on leaf K because even the check plots had leaf K levels near or greater than 2.0%. However, some combinations of N and P fertilizers decreased leaf K at some sites.

Terman and Noggle (1973) observed that leaf N increased with rates of applied N which also gave higher concentrations of P, Ca, and Mg, but a lower K concentration. They explained that increases in P concentration with increased applied N are usually observed in soils having high available P or when high rates of P have been applied. On the other hand, the increase in Ca and Mg with the amount of applied N may be due to the usual effect of NO_3^- in increasing total inorganic cations in plants.

Some of the researchers cited here as well as many others have reported the marked effects of applied N on N uptake and concentration and, as well, on the uptake and concentration of P and other cations and, finally, on yield.

Terman et al. (1977) evaluated the N x P interaction. They pointed out that a number of researchers have attributed the effect to increased root growth, physiological effects of N in the plant, and the acidifying effects of N fertilizers, especially of NH_4-N. The physiological effect of N on P or of P on N in the plant can be related to amino acid synthesis in which P and S are also involved.

Leikam et al. (1983) reported that this enhancement has been most consistently observed when N was supplied as NH_4^+-N rather than as NO_3^--N. Increased P availability may result from acidity produced by nitrification of ammoniacal fertilizer in the retention zone. Also, lowering of the rhizosphere pH due to exchange of the H^+ ions from the root for NH_4^+ ions in the soil could increase P availability and uptake. It has been noted that NO_3^- absorption increased rhizosphere pH due to exchange of OH^- and HCO_3^- ions for NO_3^- ions in the soil solution which leads to a reduced P availability. These researchers studied the effects of N and P application methods and N sources on the nutrient composition and yield of winter wheat. The results suggested a synergistic effect between N and P dual placed, not simply a positional availability effect due to deeper placement into a more moist soil. A greenhouse experiment with wheat showed that NH_4^+-N enhanced P uptake more than NO_3^--N when banded with ammonium polyphosphate. It was important to apply N and P in intimate contact, because separate band applications resulted in lower P concentrations.

The synergistic effect of N on Zn uptake also has been noted. Soil acidification and enhanced root proliferation can be contributing factors. Applied N is also responsible for greater uptake of other nutrients from the soil. This is probably due to the greater crop yield despite the dilution effect. Dilution of P, Zn, and Mn had been imposed by N increments but they were more than compensated for in total uptake by the yield increases (Olson and Kurtz, 1982).

Plant analysis was initially regarded as a biological test to assess the availability of plant nutrients in the soil. According to Koch et al. (1970), the so-called available P and K and other nutrients as measured by soil tests at best serve as an index to what is actually available to plants. They evaluated the Q/I (quantity/intensity) technique to determine available K to corn on a field basis by studying the relationship between leaf K and exchangeable K. They found that leaf K increased with K fertilizer levels but this relationship was affected by the lime levels, which indicated that either Ca or Mg competed with K for uptake or that liming reduced available K.

The relationship between leaf K and the pool of labile soil K was unaffected by the lime levels; hence, leaf K was closely related to the pool of labile K in the soil. They concluded that labile K is a good index of the amount of K available to corn. They also suggested that the pool of K is not the important criterion of K adequacy as such, but is more related to K uptake through its effect on diffusion and mass flow of K to the sites of uptake. However, a host of other factors (temperature, moisture, oxygen tension, extent of the root system, etc.) will affect the adequate supply of K from the labile pool.

Rehm et al. (1983) reported the effects of the applications of P, K, and Zn on the nutrient composition of corn grown for grain and silage on an irrigated sandy soil in Nebraska. Both grain and silage yields were increased by the application of P while the application of K and Zn had no significant effects. Leaf P increased with applied P in both systems, but the increase was linear in some years and curvilinear in others. The R^2-values for the relationships between leaf P and applied P were relatively high in all years but leaf P levels varied significantly from year to year. The year x P rate interaction was not significant, indicating that the substantial year-to-year fluctuation in environment was the chief factor in the variability in leaf P. Application of fertilizer K increased leaf K but leaf K also varied among years. Because leaf K did not decrease with time and no yield response to applied K occurred, the soil was capable of supplying adequate K to the crop.

Miranda (1981) ascertained the effects of the deficiency of one element on the critical concentration of another by analyzing data from experiments in which different rates of either N and P fertilizers, N and K fertilizers, or N and PK fertilizers were applied. He regressed the N, P, and K leaf nutrient levels on the levels of applied fertilizers. In the NP experiments, the regressions of leaf N and leaf P showed that N fertilizer had significant, positive, and curvilinear effects on both leaf N and P. The P fertilizer generally had negative, linear effects on leaf N and significant, positive, and curvilinear effects on leaf P in most experiments.

In the NK experiments, he found that N fertilizer had the effects already described on leaf N, whereas K fertilizer had a mostly linear, negative effect on leaf N. Lastly, the N x PK rates experiments showed that N fertilizer had the effects already explained and PK fertilizer generally had a negative effect on leaf N. He also concluded that, because the N, P, and K fertilizers had differential effects on the critical %N and %P of the grain and leaf, critical nutrient percentages should be studied at varying rates of all three fertilizers.

Soil and crop management factors

Dumenil and Hanway (1965) outlined the effects of several factors on nutrient concentrations of corn leaves. They reported that an increasing stand level decreased leaf N, had little effect on leaf P (except indirectly through the effect on leaf N), and often increased leaf K slightly. The increased need for fertilizer N for higher stand levels also required additional P and K, but this effect was not due directly to the increased stand. Weeds probably have a similar effect at higher stand levels.

Early fall-applied or late sidedressed N can be positionally unavailable during the rapid growth stage prior to silking due to weather conditions. Plowed-under P and K are more available to corn than disked-in or row-applied P and K, especially if July rainfall is low. Position of corn in a crop sequence also affects leaf concentration since available

N decreases with monocropping. Likewise, K availability decreases after alfalfa is removed for hay causing a low leaf K for first-year corn. Rootworm and corn borer damage may decrease leaf nutrient levels, especially if rainfall has been low.

Voss (1969) evaluated the effects of management factors on corn leaf composition by regression analysis. He found that leaf N decreased as number of years from meadow increased and decreased as plant population increased. The negative effect of plant population decreased at higher rates of N. Similarly, weeds had a negative effect on leaf N. Leaf P decreased with increasing plant population, weed growth, and number of years from meadow. The effect of past cropping was modified by a negative interaction with applied N; applied N increased leaf P more in first-year corn after meadow than in fifth-year (continuous) corn. Voss also reported that leaf K was increased by an increasing number of years from meadow, weeds, and a later planting date.

Rehm and Wiese (1975) evaluated methods of N application on irrigated sandy soils and found that, except for N application before planting, the method of N application had no effect on leaf N. They reported that a low leaf N level of corn receiving only preplant N indicated that some N was not available to the crop at silking time. Conversely, the method of N application had a significant effect on corn yields. Highest yields were obtained from a sidedressed N application in conjunction with N applied in the irrigation water. Under this condition, more NO_3^--N was present above the 150 cm depth in the soil which was reflected in higher N recoveries in the above-ground portion of the crop.

Bigeriego et al. (1979) determined the effect of the method of ^{15}N-depleted application on its uptake, translocation, and utilization in irrigated corn. With N applied at planting time, they observed that roots contained less of the depleted ^{15}N fertilizer than crowns and the latter had less than foliage throughout the season at all application rates. But, if sidedressed, crowns had more N from the fertilizer than any other plant part and substantially more than with application at planting time at all N rates. They suggested that delayed N application of the fertilizer channels more of the fertilizer N to grain and results in less immobilization in vegetative parts. They added that the percentage of NO_3^--N from fertilizer in above-ground parts increased with sidedressing and decreased with planting time application, indicating a more active uptake of fertilizer N during grain filling with delayed application of N. They concluded that application of much of the fertilizer N should be delayed until an active crop root system exists in the soil for N absorption, especially under humid climate or irrigation where adequate moisture is assured to carry the N into the primary rooting zone of the crop.

Bar-Yosef and Kafkafi (1972), who studied the effects of N and P fertilization on the rates of growth and nutrient uptake of irrigated corn, observed that most of the P was concentrated in the upper 40 cm of the soil and that, after two weeks of its application, about 40 to 50% of the P was transformed to compounds nonextractable with $NaHCO_3$. Differences between soil samplings taken at different times evidenced that plant uptake rather than soil fixation was the main cause of reduction in extractable soil P.

Their analyses showed that, of the NH_4^+-N applied in the 200 and 400 kg N/ha treatments, 100% and 70%, respectively, were converted to NO_3^--N in two weeks. Leaching was assessed by sampling the soil at different dates and two soil depths but little occurred under their experimental conditions. Hence, they concluded that denitrification was the mechanism that accounted for the N losses. They considered that the simultaneous conditions causing heavy N losses by denitrification could be: (1) high NO_3^--N levels, (2) high levels of microorganisms operating near the roots on root exudates, (3) high levels of fresh organic matter, and (4) loci of anaerobic conditions due to irrigation.

Recently, the no-till technique and its effects on corn production has been studied by researchers. Estes (1972) determined the elemental composition of corn grown under no-till and conventional tillage to observe the efficiency of uptake of several elements. In his opinion, no-till may alter the intensity and balance of nutrients because a large portion of fertilizer and lime is broadcast on the soil surface which may cause more or less than optimum nutrient obsorption. He stated that uptake of applied nutrients might be very efficient if the root system proliferates near the soil surface. Significantly higher leaf concentrations of Ca, Mg, Zn, Mo, B, and Al were associated with conventional tillage, but leaf K was higher under no-till. Leaf P, Fe, and Mn levels were the same under both systems. The higher Ca and Mg uptake under conventional tillage suggested that more frequent liming is needed for the no-till conditions.

Lal (1979) used corn leaf composition to assess the fertilizer use efficiency of no-till and conventional tillage treatments for a tropical soil. He reported that no-till outyielded the conventional tillage in all three seasons. Leaf N was only affected by level of N application and the differences between tillage treatments were not significant. Leaf P was not affected by tillage or fertilization treatments. Leaf K was not affected by fertilizer treatment but was higher on no-till plots than on plowed plots. Levels of leaf Ca, Fe, and Mn were little affected by tillage treatments. The correlation between leaf composition and yield showed that leaf N was more highly correlated with yield in the plowed than in the no-till plots, while leaf Ca and K were more correlated with yield in the no-till treatments.

Because high rates of N loss have been observed from N fertilizer applied directly on the surface in no-till corn, Mengel et al. (1982) assessed the effect of the placement of N fertilizer for no-till and conventional-till corn. They found that injecting NH_3 or urea-ammonium nitrate (UAN) solutions below the surface gave higher yields and leaf N levels than surface applications of UAN, NH_4NO_3, or urea, showing an increase in N use efficiency from subsurface N placement.

The presence of hardpans or tillage pans may restrict utilization of subsoil moisture and nutrients and may limit corn yields. Chancy and Kamprath (1982) studied the effects of deep tillage on corn response to N in a soil having a 5-7 cm thick tillage pan. The results of the 1978 season showed that leaf N was significantly increased in the chisel-plow and subsoil treatments as N rate was increased. Nitrapyrin had no effect on leaf N except in the chisel-plow treatment. In 1979, the lower level of N in the upper soil horizon was reflected in leaf N levels lower than in 1978. In 1979, subsoiling significantly increased leaf N above that of conventional tillage which suggested that root extraction of soil N occurred below the tillage pan. Leaf N in the chisel-plow treatment was lower than that of the subsoiled treatment which may be due to leaching of NO_3^- beyond root proliferation in the chisel-plow treatment. In both years, yields were greater in the deep tillage treatments and the authors attributed these to the utilization of moisture below the disrupted tillage pan during droughty periods in July and August and to the utilization of N leached below the tillage pan.

Voss (1962) also included in his regressions some management variables such as planting date and plant density. He found that leaf P was decreased by later planting and higher plant density. The interaction between planting date and applied N showed that the initial effect of applied N was to increase leaf P at an early planting date, whereas it decreased it at a later planting date. He reasoned that this effect may be due to temperature effects on root growth and dissolution of applied P. Leaf P was also affected by significant interactions between plant density and applied N as well as planting date and applied P.

Weather and other environmental factors

The relationships among nutrient concentration, yield, and nutrient supply which can be diagnosed by plant analysis are affected by the time and spatial variability of weather and weather-affected variables. Bates (1971) argued that this variability may limit the interpretation of plant analysis results if it affects nutrient concentrations at the time of sampling and plant responses to applied nutrients.

Dumenil and Hanway (1965) generalized that the weather conditions in the 20-30 days prior to sampling influence the availability of soil and applied nutrients and, consequently, the leaf analysis results. They observed that moisture conditions of the plow layer are particularly important because it contains most of the available N from organic matter, P, and K. Drying of this layer usually decreases the leaf levels of these elements.

They added that drought conditions usually decrease P and K uptake more than N uptake, while wet, cool weather in late June and July slows release of N and P from soil organic matter and manure, increases leaching and denitrification of N, and limits root growth, all of which reduce leaf nutrient levels. Availability of fall-applied or spring-preplant N with above normal rainfall early in the season or of late sidedressed N with below normal rainfall after application may be decreased for corn in July. Likewise, plowed-under P and K are more available than disked-in or row-applied P and K if July rainfall is low.

Voss (1962), as already cited, characterized the effect of weather by using a stress day criterion proposed by Shaw (1961). In this method, a stress day was any day in which the available moisture was below 40% of the maximum available moisture capacity in the surface foot and in the root zone. Available soil moisture for any day was computed by utilizing the amount of available moisture in the root zone, rainfall, depletion of soil moisture, and estimated evapotranspiration. Because the weather effects depend on the occurrence of certain factors of weather in relation to the stage of growth, he divided the growing season into various periods. The stress days were accumulated over four continuous growing season periods of 5, 4, 3, and 6 weeks in length, designated as D1, D2, D3, and D4, respectively.

The stress days for the D2 and D3 periods and their interaction significantly affected leaf N but the effect of D2 was positive while that of D3 was negative. A high incidence of stress days in D2 affected the change in leaf N due to applied N by decreasing the positive response. The initial response to N at low stress day incidence was higher than at high stress day incidence, probably because of more available N in the moister soil. Voss also found that the increase in leaf N due to applied P decreased with increased number of stress days. High incidence of stress days in all periods, hence, decreased leaf N.

The D2 and D3 periods had positive and negative significant effects on leaf P, respectively. A high incidence of stress days in both periods decreased leaf P and this effect was not influenced by levels of other factors. Stress days in periods D1 and D3 negatively affected leaf K but no interactions with other factors occurred. A high incidence of stress days in all periods decreased leaf K.

A similar stress day criterion was used by Powell (1968). He found a negative correlation between stress days and both leaf N and leaf P in most of the site-years studied. However, he did not include the stress day index in the regression analysis.

Voss (1969) investigated the effect of weather on leaf N, P, and K of corn in western Iowa by using Shaw's (1968) modification of Laing's relative photosynthesis index which is based on estimated relative turgidity. The data required to compute this index are: (1) determination of period of growth most susceptible to water stress, (2) estimation of daily soil moisture as computed with Shaw's water balance method, (3) estimation of daily relative turgidity (RT) of the canopy using daily soil moisture and pan evaporation data, and (4) transformation of RT into relative photosynthesis (P/Po). The ratio P/Po represents the proportion of photosynthesis with a given RT compared with that at full turgor.

He also divided the growing season into three periods but the partitioning did not improve the correlation with yield and no attempt was made to correlate the partitioning of the index with leaf concentrations. The index, therefore, was computed for the period from 6 weeks before to 3 weeks after silking.

The regression of leaf N on the stress index and other variables showed that leaf N increased as soil moisture increased. The significant interaction of the stress index with rates of applied N indicated that, under high stress, lower rates of fertilizer N increased leaf N more than at low stress but the rate of change was greater under high stress, so at high rates of N, the increase in leaf N was less than at low stress as fertilizer N increased.

Increased soil moisture also increased leaf P and the leaf P response to applied P was affected by soil moisture. Fertilizer P increased leaf P less as soil moisture increased. However, leaf K decreased as soil moisture increased and no significant interactions occurred between the stress index and other variables on leaf K.

The effects of barrenness on leaf nutrients were also evaluated in this study. It had a significant, negative effect on leaf N, a slight effect on leaf P, and no effect on leaf K. He considered that barrenness resulted from adverse effects of some management and environmental factors on the corn.

Miranda (1981) evaluated the effects of soil moisture on corn leaf critical percentages. The soil moisture stress used was that proposed by Dale and Shaw (1965) and later modified by Shaw (1974). This index is computed as Stress = 1 - ET/ETP, where ET and ETP are actual and potential evapotranspiration, respectively. If the soil moisture supply satisfies the atmospheric demand for water, then ET is equal to ETP and no stress occurs on that particular day; if no ET occurs because of low soil moisture, the index reaches its maximum value of 1.0. The stress index can attain values between 1.0 and 0 and the daily values are summed over 17 five-day periods, from 40 days before to 45 days after the 75% silking date. The index value for each period is weighted by a factor that accounts for the differential effects of stress on corn phenology. This index was identified with the DV symbol.

In a combined analysis of a series of N-rates experiments in Iowa, the regression of leaf N on the DV index and applied N showed that leaf N decreased slightly as DV increased (higher stress). In a series of NP-rates experiments, he found that leaf N and leaf P of first-year corn after soybeans decreased as DV increased, whereas in second-year corn, the effects of DV varied from positive at low rates of N and P fertilizers to negative at moderate to high rates of both.

Estrella-Chulin (1984) studied the effect of applied and residual P and the moisture stress index of Shaw (1974) on corn yield and leaf P. He found that applied P tended to increase leaf P but the magnitude of the response varied from year to year; this effect was mostly explained by the variability of moisture stress among the years. In those years in which there was no stress, leaf P was high and a clear response to the treatments was observed. As the moisture stress index increased, leaf P decreased in those treatments with adequate supply of P, that is, moisture stress had a larger effect on leaf P at high rates than at low rates of applied P.

Asghari and Hanson (1984) used regression analysis to relate the corn leaf N concentration to the rate of applied N and to precipitation and heat units during June and July. They reported that increasing heat units in these months increased leaf N concentration, seemingly because of reduced plant growth and development under high heat stress. Data from corn after wheat showed that leaf N increased as June precipitation decreased which was also attributed to reduced growth from moisture stress. On the other hand, leaf N increased as July precipitation and applied N increased. Similar effects were observed in data from corn after alfalfa except that July precipitation did not affect leaf N.

The influence of the soil moisture condition (excess or deficiency) and drainage on nutrient uptake and concentration in corn has also been studied in controlled irrigation or lysimeter experiments. Shalhevet and Zwerman (1962) evaluated the corn response to N under variable drainage conditions in a lysimeter. They reported that corn plants attained higher N, P, and K concentrations under well-drained conditions than under the waterlogged treatment. Additions of nitrate-N improved corn yields in the poorly drained lysimeter. Apparently, leaching or denitrification explained this response.

Likewise, Lal and Taylor (1970) evaluated the same effects in a field lysimeter. They concluded that nutrient uptake under wet conditions can be affected by external or internal factors. External factors such as soil-reducing conditions tend to increase the solubility of heavy metals like Al, Fe, and Mo. Denitrification may change the soil pH and alter biochemical processes depending on the pH. Internal factors involving physiological or morphological changes are also important. A limited root system contacts a small soil volume and, hence, less interception of nutrients occurs. Excess CO_2 in the rhizosphere causes suberization of root hairs, decreasing their permeability to water and nutrients. Inadequate aeration may inhibit translocation of nutrients within the plant and antagonistic effects among nutrients may occur in the soil and within the plant.

They observed that the uptake of N, P, and K by corn was highest in the well-drained treatments. Increasing water table depths and N, Cu, and Zn fertilizers had significant positive effects on leaf N and P levels. The effects of these factors were independent since no interactions were detected but the effect of N fertilizer was the dominant one. A 96-hour flooding decreased leaf N and leaf P while higher levels of soil N and a constant water table decreased leaf K.

They explained that the reduced uptake of N under intermittent flooding and constant water table depth was due to loss of soil N by denitrification and by reduced N mineralization because higher concentrations of ammoniacal-N were found in the drainage water from the 15-cm water table depth than from the 30-cm depth. Besides, greater concentrations of gaseous N were found in soil air removed from the former than from the latter treatment. The lower leaf P under wet conditions are attributed to decreased P solubility since Mn solubility increased in lysimeters with a water table. Hence, Fe and Al could also be more soluble leading to the formation of nonsoluble P compounds. The lower K uptake was probably explained by reduced soil aeration.

With regard to soil aeration, Lawton (1945) and Shapiro et al. (1956) demonstrated reduced uptake of some nutrients such as K, Mn, P, and N if soil oxygen was reduced. Shapiro et al. found higher concentrations of those nutrients in the roots as compared to the tops of corn plants, suggesting that reduced oxygen affected nutrient translocation.

Rhoads and Stanley (1973) assessed the effect of soil moisture tension in the plow layer on the yield response of three corn hybrids. Yield was increased each year when irrigation was supplied at 0.2 or 0.3 bar tension instead of 0.6 bar. Higher yields were obtained when tension was kept at <1/3 bar. However, nutrient contents of corn leaves were not affected by irrigation treatments or increased N application, but they remarked that mixing of fertilizer in the plow layer may have caused a concentration of roots in the plow layer and, thereby, a higher water demand in that zone.

Liao and Bartholomew (1974) carried out a series of greenhouse experiments to study the relationships between water uptake and the absorption of NO_3^- (using ^{15}N as a tracer) by young corn plants. The mechanisms illustrated might be useful to understand these relationships under field conditions.

In one experiment, they studied the absorption of $^{15}NO_3$ at two depths (5 and 30 cm) under wet and dry soil conditions. They observed that, in both soil moisture conditions, ^{15}N was mostly absorbed from the deep than from the shallow layer and that $^{15}NO_3$ remained in the root zone when soil moisture was not favorable, although plants were obtaining enough water from deeper soil for normal growth. This suggested that the absorption of $^{15}NO_3$ was related to the soil moisture conditions. Owing to surface evaporation, more total water would be expected to be absorbed and transpired from the deep than from the shallow irrigation, while the surface layer would be expected to contain little water at the time the plants showed water stress.

These workers observed that, in some of the studied systems, the rates of NO_3 absorption were greater than those of water, while the opposite occurred in other systems. They argued that plant factors can be responsible for these differences and reasoned that N transport by diffusion can operate only when physiological factors differentiate between the absorption of water and NO_3, consequently causing a concentration gradient. They demonstrated that physiological discrimination in favor of NO_3 took place; conversely, absorption of NO_3 less than that expected from mass flow indicated that discrimination against NO_3 also occurred.

Olson and Kurtz (1982) pointed out that the nitrate that moves down with the percolating water becomes important in a dry season. When surface horizons dry out, NO_3^- in the lower horizons is a source of N during the later growth stages of the crop, since little or no NH_4^+ exists at these depths.

Hanway and Olson (1980) remarked that P uptake is affected by soil moisture because plants cannot take up P from a dry soil. In most soils, P availability is highest in the surface plow layer and much lower in the subsoil; therefore, if the surface dries, plants suffer from P deficiency although the subsoil is still moist and plants show no moisture stress. Conversely, excessive moisture can cause poor aeration and reduced P uptake. Under this condition, allocation of fertilizer in bands near the plants can produce a high nutrient concentration which would enhance plant growth in poorly drained soils. Topdressing P fertilizer, if soil surface remains dry after application, is not an effective practice for annual crops.

Weather characterization

Weather-related factors exert definite effects on soil and plant processes modifying, at the same time, the effectiveness of the soil and crop management practices. The complex interactions taking place among all those factors determine the ultimate plant responses such as nutrient uptake, nutrient composition, growth, and the final economic yield.

Multiple regression analysis has been a method widely used to quantify the effects of weather factors on crop yields. In studying this relationship, one approach has been to employ meteorological parameters such as precipitation or temperature in a regression context. Monthly averages, maximum or minimum values, and values for specific intervals or phenologically related periods have been employed as independent variables in the regression equations. Others have been concerned with the changing impact of the weather factors as the growing season progresses. Fisher (1924) even introduced a polynomial summation technique which allows estimation of the effects of weather factors corresponding to small subdivisions of the growing season without increasing the number of independent variables in the regression equation. Furthermore, Hendricks and Scholl (1943) simplified and adapted this technique for the assessment of two or more weather factors as well as their respective interactions. Research by Runge and Odell (1958) and Runge (1968) are examples of the use of this technique.

Agricultural economists and agroclimatologists also have carried out significant amounts of work to identify primarily the variability in crop yields that is associated with climatic trends among years and large areas. For example, Dale (1948) studied the effect of rainfall in different phenological periods of the corn crop in five Iowa counties throughout a 26-year time span. He computed simple correlation coefficients between different rainfall periods and corn yields using 75% silking as a reference point for the crop calendar. He found that the summation of the rainfall corresponding to the period from six weeks before to three weeks after silking accounted for the greatest effect of rainfall on corn yield. However, he observed that the rainfall for the 9-week critical period had a significant curvilinear effect in only two of the five counties.

Thompson (1969), using data from five Corn Belt states, regressed corn yields on weather variables and a technological trend. He noted that the technological trend and July rainfall explained most of the variability, although June, July, and August temperatures and preseasonal temperatures were also important. Highest corn yields were associated with below-normal temperature and above-average rainfall in July.

Casanova (1979) used regression analysis to study the effects of rates, sources, and placement method of P fertilizer as affected by soil, weather, and management factors. For the weather factors, he included in the combined analysis of the data from four experiments the DV moisture stress index and the amounts of rainfall corresponding to the 46-day period (PPT46) starting three days after planting and the amount of rainfall for a 75-day period (PPT75) starting 6 weeks before the 75% silking date.

He reported that maximum yield occurred at PPT46 = 4.2 cm which was below the mean (11 cm). He regarded the effect as logical since most research has shown that highest corn yields occurred when the early season had below-normal rainfall and July and August had above-normal rainfall. Maximum yield occurred at PPT75 = 31 cm which is 8 cm above the mean. He pointed out that a significant feature of his final yield models was the dominance of the weather variables since they interacted with all other variables but one. Although DV and PPT75 did not occur together in the same model, but were used separately in alternate models, the regression coefficients of most variates in the two final yield models were similar, thus indicating that DV and PPT75 were about equally as effective in explaining yield variability.

Using the Hendricks and Scholl's modification of Fisher's polynomial summation technique, Runge and Odell (1958) and Runge (1968) divided the growing season for corn into 2-day and 8-day periods and used the summation technique for creating independent variables for a multiple regression equation. They also compared the use of polynomials up to the fourth degree.

Leeper et al. (1974) illustrated the use of this technique to assess the effects of the interaction between a seasonal variable (time-independent) and a weekly or time-dependent variable as well as the interaction between two time-dependent weather variables.

Another approach considered that factors such as seasonal rainfall or mean temperatures poorly represented the environmental conditions and their effects on crop yields. Perrin and Heady (1975) quoted that Thornthwaite recognized that the effects of rainfall and temperature on plant growth must depend on the amount of available soil moisture. As a consequence, moisture balance models have been developed which resulted in weather indexes that integrated the effects of soil and weather factors in critical cropping periods. Instances of this approach are the series of studies in Iowa by Dr. R. H. Shaw and coworkers which culminated in a refined moisture stress index proposed by Shaw (1974). Some others such as Morris (1972), Henao (1976), and Pena-Olvera (1979) have further modified or adapted Shaw's computer program to obtain excess moisture indexes.

Morris (1972) presented a very comprehensive review of the weather-plant relationships as well as of the principles and procedures involved in the definition and computation of weather indexes. A more recent review was also performed by Villalpando-Ibarra (1983).

From his review, Morris (1972) concluded that both excess and insufficient soil moisture conditions can have an adverse effect on corn yields. The deleterious effect of excess moisture is greater in the immediate post-planting period, while moisture stress affects corn yield the most starting in the period prior to anthesis and continuing during the grain filling stage.

Moisture stress indexes   Dale and Shaw (1965) developed a computer program to calculate a moisture stress index which has produced reasonable results for Iowa corn yield models. Morris (1972) modified this program to fit the corn yield study data and to allow for the computation of an excess moisture index.

According to Morris (1972), the computation of this soil moisture stress index is based on the daily values of plant available water percentage (PAW) and pan evaporation loss. These values can be related in different ways to obtain daily estimates of the relative efficiency of the net photosynthetic process.

The approach used by Morris sums the relative transpiration rates (RTR) for each day in the index period. The RTR (RTR = STET/ET, where STET is stressed evapotranspiration and ET is unstressed evapotranspiration) is determined from the relationship proposed by Shaw (1963) which is based on the greater of the PAW percentage for the root zone or the surface foot and the atmospheric demand intensity as given by the daily pan evaporation values. Morris (1972) designated the summation of the daily RTR values as the DEFCT index.

In order to account for differences in daily photosynthetic rates, Morris (1972) multiplied the index DEFCT by daily evapotranspiration values. The weighted index was designated as DEFCTX. Taking into account that Claassen and Shaw (1970) had demonstrated that moisture stress may have a differential effect depending on the growth stage at which it occurs, Morris introduced a growth stage weighting factor. The growth stage-weighted index was designated by Morris as DEFCTW. Another modification implemented by Morris was to weight the DEFCT index by both energy (pan evaporation) and growth stage. The resulting index was designated as DEFCTV. X1 was a new index which was similar to DEFCTV but the energy-weighting factor was obtained from the evapotranspiration/pan evaporation ratio through the growing season that was proposed by Shaw (1963).

Morris (1972) evaluated these indexes by comparing their correlations with corn yields. He found that the index that was weighted by both energy and growth stage (DEFCTV) was more strongly associated with yields than the unweighted one (DEFCT) or those weighted by either one of the two factors (DEFCTX and DEFCTW). He concluded that the DEFCTV index was the most appropriate for inclusion in his subsequent regression analysis.

Thereafter, Henao (1976) recomputed these indexes after revising the KX values (soil redistribution classes) based on subsoil permeability classes. He used abbreviated symbols for the newly computed indexes: DT for DEFCT, DV for DEFCTV, DW for DEFCTW, and DX for DEFCTX. In his study, he also included the total rainfall for a 75-day period (PPT75) starting 6 weeks before 75% silking.

Henao's (1976) results showed that the DV index was highly correlated with DX and somewhat less with DW and DT, while DW and DT were also very highly correlated. On the other hand, PPT75 was less correlated with all the other indexes ($r = 0.49$ to 0.57). He also found that the moisture stress index weighted by both energy and growth stage (DV) was more strongly correlated with yield than the other indexes; hence, DV was chosen for inclusion in his corn yield regressions.

From his study, Henao suggested that the indexes would be improved by using additional and/or improved input data as well as by improving the estimation of water runoff. With this in mind, Pena-Olvera (1979) tested five major modifications of the DV index which were: (1) reestimation of PAWC, (2) use of a 75-day instead of the 63-day stress period, (3) use of an improved growth stage weighting factor proposed by Shaw (1974), (4) reestimation of starting plant available water (PAW), and (5) use of water runoff corrections by slope, previous crop, and/or infiltration.

He evaluated different combinations of these modifications by computing alternative regression models. It was observed that DV3 (Henao's DV including the first four modifications) and DV4 (same as DV3 but with reestimated PAW corrected by antecedent rainfall) produced regressions with similar R^2-values. He chose DV4 for inclusion in the regression of yield on several soil and management variables. It had significant interactions with subsoil permeability, subsoil root rating for root growth, PAWC, plant density, weed infestation, planting date, silking date, crop sequence, and soil pH of the plow layer.

Avilan-Camejo (1978) computed Shaw's stress index for each of the seventeen 5-day periods considered for the growth stage weighting of this index. He evaluated seven different combinations of the 5-day periods depending whether the stress took place before or after silking time. Simple correlation coefficients among the seven indexes were computed. He found that, in general, they were highly correlated with each other. Because the combination of 5-day stress periods from three weeks before to three weeks after silking was the period of time which was most correlated with the other periods and, because the period closest to silking is the stage most sensitive to moisture stress, the index for these periods was chosen as the moisture stress index to use.

Excess moisture indexes   Morris (1972) reviewed the literature about some of the potentially detrimental chemical and physiological mechanisms due to excess moisture that could be operational in the experiments reported. However, he did not find that any specific mechanism was the main source of the yield reductions from excess moisture. Because reduced aeration was a common condition, he modified Dale and Shaw's (1965) computer program to include the estimation of the fraction of the root zone that was below some assumed critical percentage of air-filled pore space. That fraction was summed over a 46-day period starting 3 days after planting. The assumed critical percentages were 7.5, 10.0, 12.5, and 15.0. The indexes derived from each assumed percentage were designated as EXMO1, EXMO2, EXMO3, and EXMO4, respectively.

Another excess moisture index, MOISDV, was computed by adding the number of days, within the 46-day period, that any layer in the root zone was above field capacity. The indexes MOISDV, EXMO2, and EXMO4 were also weighted by a growth factor to account for the differential effect of excess moisture with plant development, using the weights based on data of Ritter and Beer (1969). Lastly, a third index (AIRVOL) was computed by summing the surface layer air space over a 21-day period starting three days after planting.

From the evaluation of these indexes, Morris (1972) concluded that EXMO2 was most appropriate for regression analysis and, when weighted, its usefulness was improved although EXMO3 was almost as good as EXMO2.

Subsequently, Henao (1976) tested a set of different critical percentages of air-filled pore space. The percentages were 12.5, 15.0, and 17.5, and the indexes so computed were called EXMO2, EXMO3, and EXMO4, respectively. The EXMO3 index was multiplied by the growth stage factor and listed as the EXMO3V index. From the comparisons of these indexes, he selected EXMO3V (abbreviated as EM3V) to include in his final prediction model.

Using Henao's EM3V index, Pena-Olvera (1979) computed a new set of excess moisture indexes by applying the same modifications that he used for the stress moisture indexes. He concluded that adjustments for time period, weighting factor, and PAW had no effect on the indexes as revealed by their very similar r-values with yield. Because of the high intercorrelation between these indexes, Pena-Olvera then tested three of them in alternative regression models. He reported that the R^2-values were very similar, indicating that the modifications applied did not improve this index. Therefore, the EM34 index (corresponding to the DV4 index) was included in the final yield prediction model.

In the final regression models of Henao (1976) and Pena-Olvera (1979), the excess moisture index had a significant, negative, linear effect on corn yield but it did not interact significantly with any other of the variables studied in their respective data sets.

DATA SOURCES AND PROCEDURES

General Description

The data used in this study included the same soil, weather and management variables that were previously described by Henao (1976) and recomputed and transformed by Sridodo (1980). This data set was collected under the supervision of Dr. Lloyd C. Dumenil of the Department of Agronomy for the Iowa Agriculture and Home Economics Experiment Station Project 1377 (replaced by Project 1958 in 1972, by project 2336 in 1978, and by Project 2574 in 1982). This project now is entitled, "Predicting corn yields of Iowa soils and their relationships with corn leaf composition."

The project was initiated in 1957 in two Iowa counties and new counties were added each year until 1962 when 15 counties were included. These counties were selected to represent the major soil association areas in the state, all of which were included except the Adair-Grundy-Haig area in southern Iowa. The methodological approach utilized was that of point-estimate sampling in which corn yield, leaf sampling, and all environmental, climatic, soil, and management variables of randomly selected sites were measured or estimated. As already stated, the information regarding field techniques, laboratory methods (except for chemical analysis of leaf samples), and methods to measure or estimate the variables were described by Henao (1976) and Sridodo (1980).

Macias-Laylle (1984) implemented some modifications of Sridodo's (1980) data set and added two new variables. The HYMAT variable was used to estimate the effects of the relative maturity of the hybrid in the area where it was planted. A second variable called HYCROSS was included to account for the effect of the type of hybrid cross (from 4-way to single-cross types).

The variable NCODE that estimated the effect of the crop sequence on N availability was recoded and renamed as NCODE1. Macias-Laylle (1984) also set new upper or lower limits for the following variables: THAHOR, MANURE, NROW, PROW, KROW, NFERT, PFERT, KFERT, STP1, and STK1. The PAWC variable was expressed in centimeters per 1.52 m rather than in inches per 5 feet. Lastly, for the purposes of this study, new upper limits were set for the variables of STN, STP1, and STK1.

Leaf Analysis and Sampling Methods

Although this project was initiated in 1957, leaf samples were collected initially in 1961 in the counties available at that time. Leaf samples were taken in all 15 counties since 1961. The leaf opposite and below the primary (top) ear shoot was sampled when the corn plants were about 40 to 90% silked, because the large number of sites included did not allow for sampling at the precise 75% silking stage as suggested in the literature. However, the date of sampling for each site was recorded as well as the estimated 75% silking. Because the sampling date (SAMDTE) did not coincide with the 75% silking date (SLKDTE), a new variable named SAMDIF was created to account for the difference between the two dates, that is, SAMDIF = SLKDTE - SAMDTE.

The leaf samples were dried and ground in preparation for chemical analysis. The finely ground leaf material was oven-dried at 65°C for 24 hours. Each sample was analyzed for N, P, and K by the Iowa State University Plant Analysis Laboratory following the procedure described by Hanway (1962b). In this procedure, a 0.5-g sample of the dry plant material is digested by boiling for 16 to 20 hours in 10 ml of concentrated H_2SO_4 plus Cu as a catalyst in a 100-ml volumetric flask on a hot plate. After digestion, the samples were diluted to a specified volume and aliquots were taken for determination of each element.

The N was determined by nesslerization. This procedure consists of detecting the concentration of ammonium sulfate in the digest solution. A yellow color is produced upon alkalinization with Nessler's reagent and the N concentration is determined colorimetrically. P was determined by a vanado-molybdate colorimetric procedure. K was determined by a flame photometer using lithium as an internal standard. All determinations were made at least in duplicate. If dissimilar readings were detected, a new aliquot was analyzed.

The two or more readings for each sample were averaged and the mean was used in subsequent computations. In some instances, the readings from the various aliquots analyzed were so dissimilar that the data for the site-year were deleted. After deletion of these plus seven site-years for which the soil moisture indexes were not computed, the final data set contained a total of 1927 site-year observations.

The leaf N, P, and K concentrations for each site-year were added along with the new SAMDTE variable to the final data deck of Macias-Laylle (1984). The variables contained in his revised deck are listed in Appendix Table A1 and the symbols and identifications of the variables included in the present study are shown in Table 1.

Weather Indexes

Soil moisture program

The soil moisture computer program as modified by Pena-Olvera (1979) was used in this study to compute moisture stress indexes, excess moisture indexes, and the precipitation indexes for the various periods of the corn growing season.

This program uses soil physical parameters to determine daily moisture reserves in the soil profile and root zone as a function of daily rainfall and evapotranspiration and to estimate the daily plant moisture status. The input data required are a starting date, rainfall and pan evaporation data, an estimate of plant available water (PAW) on the starting date for each of ten 6-inch layers, a silking date, and a redistribution class (KX) for the soil. The silking date is made to coincide with July 31 in order to adjust actual dates to program dates. The adjusted silking date must allow the location of the evapotranspiration/pan evaporation ratio properly with respect to corn phenology. Additional inputs for the program are: a table of runoff loss values, ratios of evaporation to open pan evaporation relative to corn phenology, and evapotranspiration adjusted for moisture stress.

The program produces a number of different moisture stress and excess moisture indexes, total and growth stage weighted precipitation in selected phenological periods, and the daily soil moisture balance for

Table 1. Symbols and identification of the variables included in the regressions of corn leaf concentrations of N, P, and K on soil, management, and other variables

Variable symbol	Variable identification
LEAFN	Concentration of N in the corn leaf, %
LEAFP	Concentration of P in the corn leaf, %
LEAFK	Concentration of K in the corn leaf, %
SLKDTE	75% silking date, coded July date or August date + 31
SAMDTE	Leaf sampling date, coded July date or August date + 31
SAMDIF	Difference between silking date and leaf sampling date; SAMDIF = SLKDTE - SAMDTE
BARR	Barren plants, %
	Environmental group
CRW	Corn root (rootworm) damage rating, coded 10 (none) to 60 (very severe)
CB1	First brood corn borer, cavities/10 plants
CB2	Second brood corn borer, cavities/10 plants
WEEDS	Total weeds, grassy + broadleaf, kg/0.1 ha
	Tillage and planting group
CULT	Rotary hoed and cultivated, number of times
PLOW	Time of plowing, coded fall = 0, spring = 1, none = 2
TILLAFT	Tillage operations after plowing, number of times
PLDEN	Plant density, number of plants/0.01 ha
PLDATE	Planting date, coded days after April 20
PLMETH	Planting method, coded drilled = 0, hill dropped = 1
ROWWID	Row width, coded row width in cm minus 71 cm
ROWSLP	Slope of corn rows through harvest area, %
HYMAT	Relative hybrid maturity, coded early = 1, adapted = 3, and late = 5
HYCROSS	Hybrid cross, coded, double = 1, 3-way = 2, modified single = 3, and single = 4
	Fertility management group
MANURE	Manure applied, metric tons/ha
NROW	N applied in row fertilizer, kg N/ha
NBDCT	Total N fertilizer other than NROW, kg N/ha
PROW	P applied in row fertilizer, kg P/ha
PBDCT	Total P fertilizer other than PROW, kg P/ha
KROW	K applied in row fertilizer, kg K/ha
KBDCT	Total K fertilizer other than KROW, kg K/ha
TILE	Distance to tile line, coded 61 m minus distance in m

Table 1. (Continued)

Variable symbol	Variable identification
KCODE[a]	Crop sequence code for K availability, coded 0-60
NCODE1	Crop sequence code for N availability, coded 8-40
NRES1	Total N (manure + fer.) applied previous year, kg N/ha
PRES1	Total P (manure + fer.) applied previous year, kg P/ha
KRES1[a]	Total K (manure + fer.) applied previous year, kg K/ha
PRES2	Total P applied 2 years previously, kg P/ha
KRES2[a]	Total K applied 2 years previously, kg K/ha
PRES3	Total P applied 3 years previously, kg P/ha
	Soil tests group
PH1	Soil pH, coded (soil pH*10) - 50
STN	Soil test N (field moist), pp2m N
STP1	Soil test P (field moist), pp2m P
STK1	Soil test K (field moist), pp2m K
STP2	Soil test P of 76-107 cm layer, pp2m P
STK2	Soil test K of 30-61 cm layer, pp2m K
	Soil group
THAHOR	Thickness of A horizon, cm
PAWC	Plant availability water capacity, cm H_2O/151 cm
DRAIN	Natural internal drainage class, coded from excessive = 10 to very poor = 90
CPL	Clay in plow layer (0-18 cm), %
CMAX	Maximum clay in subsoil, %
DCMAX	Depth to midpoint of horizon with CMAX, cm
BIO	Biosequence, coded from forest = 1 to prairie = 5
SLOPE	Slope of the site area, %
LOESS/T	Loess 51-127 cm thick over till or paleosol coded 1, all others = 0
TILL	Till parent material coded 1, all others = 0
PALEO	Paleosol parent material coded 1, all others = 0
SAND	Sand parent material in 0-127 cm profile coded 1, all others = 0
COLLUV	Colluvial parent material in loess areas coded 1, all others = 0
ALLUV	Alluvial parent material (sand >127 cm) coded 1, all others = 0
PHMIN	Minimum pH in subsoil, coded (pH*10) - 45
DPHMIN	Depth to midpoint of PHMIN horizon, cm
DCAL	Depth to top of carbonate layer, cm coded 152-depth and $\geq$152 = 0

[a]These variables were included only in the regressions of the concentrations of leaf K on these and other variables.

Table 1. (Continued)

Variable symbol	Variable identification
	Location group
TWP	S-N location, coded township number minus 65
RANGE	E-W location, coded R1E = 0 to R48W = 48

each of the ten 6-inch layers of the soil profile.

The computed moisture stress indexes as designated by Henao (1976) are: DT (unweighted index), DX (weighted by a pan evaporation value), DW (weighted by growth stage), DV (weighted by both pan evaporation and growth stage), and X1 (weighted by an evaporation factor from the Shaw (1968) relationship). The weighting factors were developed by Shaw (1974) and adapted by Pena-Olvera (1979).

The excess moisture index was computed by finding the fraction of the root zone in which the layer air space was estimated to be less than 15.0% by volume. The daily values were accumulated for each day of the 46-day index period. This index was weighted by the growth stage factor already cited and was designated as EXMO.

Soil moisture indexes computed

To determine which of the five previously mentioned soil moisture stress indexes gives the best association with each of the three leaf nutrients, all of them were computed for each of the 1927 observations (site-years).

Voss (1962) showed that moisture stress exerted a differential effect on corn leaf concentration depending on the physiological stage at which the stress occurred. However, the subdivisions of the growing season that he tested comprised 3 or more weeks each and included the whole growing season. Research previously cited has revealed that corn yields are more affected by moisture stress occurring from about 6 weeks before silking to the grain filling stage. Therefore, it was of interest in this study to compute moisture stress indexes for a number of stress periods or subdivisions of the 75-day period used by Pena-Olvera (1979).

Initially, the periods for which the moisture stress indexes were computed were: (1) a 75-day period from 42 days before silking to 33 days after silking, (2) a 40-day period from 42 days before to 2 days before leaf sampling date, (3) a 20-day period from 42 days to 22 days before leaf sampling date, and (4) a 20-day period from 22 days before to 2 days before leaf sampling date. Subsequently, the same indexes were computed for the eight 5-day subdivisions of the 40-day time period from 42 days before to 2 days before leaf sampling date.

An excess moisture index was computed for the 46-day period described previously. Subsequently, excess moisture indexes were computed for the six 8-day periods in the time period from 3 days to 51 days after the planting date. Later on, two consecutive 8-day excess moisture indexes were summed and three new 16-day excess moisture indexes were obtained.

Precipitation indexes were also obtained from the soil moisture program by summing the amounts of rainfall (in inches) in the various periods for which the stress and excess moisture indexes were computed, except that only four 8-day early-season precipitation indexes (from 3 days to 32 days after planting) were computed to avoid an overlapping with the 5-day precipitation indexes. A growth stage weighting factor was applied to the precipitation indexes computed for the four periods described previously as well as for the eight 5-day precipitation indexes. In addition, seven more 5-day precipitation indexes were computed so as to account for fifteen 5-day precipitation indexes for a 75-day period from 2 days before leaf sampling date back towards the planting date. The weather indexes computed and their respective symbols for identification are presented in Table 2.

If those periods in which the indexes were computed had reference to the sampling date, it was also made to coincide with July 31 to adjust actual dates to program dates and to have a constant phenological reference point. In computing the daily stress index, the program transforms the calendar date into a program date (IDTE) which starts on March 1 as the day number 1; thus, the adjusted sampling date or silking date (July 31) will be day 153 in the program's date. The 75-day period from 42 days before silking to 33 days after silking corresponds to the period from day 111 to day 185 in the program's dates. The computation of the various indexes accumulated for the several periods already described was achieved by setting the respective ending date in the program's date according to the number of days in the given period. For instance, for the period from 42 days to 2 days before the leaf sampling date, the program's dates included from day 111 to day 151. For the first 5-day

Table 2. Identification and symbols of the weather indexes computed for various periods of the growing season

Index period	Index symbols[a]
From 42 days before to 33 days after the silking date	PPT75, PPT75W, DT75, DX75, DW75, DV75, X175
From 42 days before to 2 days before the leaf sampling date	PPT40, PPT40W, DT40, DX40, DW40, DV40, X140
From 42 days before to 22 days before the leaf sampling date	PPTA, PPTAW, DTA, DXA, DWA, DVA, X1A
From 22 days before to 2 days before the leaf sampling date	PPTB, PPTBW, DTB, DXB, DWB, DVB, X1B
For eight 5-day periods in the 40-day period before the leaf sampling date	PPT1, to PPT8, PPT1W to PPT8W, DT1 to DT8, DX1 to DX8, DW1 to DW8, DV1 to DV8, X11 to X18
For fifteen 5-day periods from 2 days before leaf sampling back towards the planting date	PPT15-1 to PPT15-15
From 3 days after to 49 days after the planting date	EXMO, PPT46
For six or four 8-day periods in the time from 3 days after to 51 or 35 days after the planting date	EXMO1 to EXMO6, PPTEM1 to PPTEM4
For three 16-day periods in the time from 3 days after to 51 days after the planting period	EXMO12, EXMO34, EXMO56
From 3 days after to 35 days after the planting date	PPT32

[a]The first letters in the symbols stand for: PPT = rainfall for a given period; PPT-W = rainfall weighted by growth stage; DT = unweighted moisture stress index; DX = moisture stress index weighted by energy; DW = moisture stress index weighted by growth stage; DV = moisture stress index weighted by energy and growth stage; X1 = moisture stress index weighted by energy from Shaw (1963) relationship; EXMO = excess moisture index; and PPTEM = early-season rainfall for the given period.

period, the program's dates were from day 111 to day 115 and so on for the other intervals.

The relationships between the various weather indexes for the periods in which they occurred and the variability in the corn leaf N, P, and K percentages were determined. The assessment of these relationships was performed in various successive steps which will be next described.

Correlation analysis of weather indexes

A preliminary screening of the weather indexes described in the previous section was performed by computing the simple correlation coefficients between them and between them and each leaf nutrient.

In a first step, the simple correlation coefficients between the moisture stress and precipitation indexes within each of the four periods described previously were computed to assess their degree of intercorrelation. Simple correlations between indexes for different phenological periods were observed only when they were allotted to the same series of alternative regression models, that is, when they were in the same sum of squares and cross products matrix.

In the next step, all simple correlations between the five moisture stress indexes (DT, DW, DX, DV, and X1) and the two precipitation indexes (PPT and PPTW) within each of the eight 5-day periods were computed. Likewise, the correlations among the eight DV, DT, and PPT indexes were determined to test for their degree of intercorrelation. All the simple correlations between the excess moisture indexes and the precipitation indexes within each of the 8-day periods were also calculated as were those correlations between excess moisture, moisture stress, and precipitation indexes that were included in the same regression models.

Lastly, all of the simple correlations between the various weather indexes and each of the leaf nutrients were computed.

Development of the quadratic base model

A quadratic base model was derived for each leaf nutrient concentration on selected soil and management variables. The final quadratic models were used to further test the weather indexes or some combinations of them. The multiple quadratic regression model fitted to the data set of this study was of the form:

$$Y = B_0 + B_1X_1 + B_2X_2 + \ldots + B_pX_p + B_{11}X_1^2 + \ldots + B_{pp}X_p^2 + E \quad , \qquad (1)$$

in which Y is the dependent variable (the leaf concentrations), X_1, X_2, ..., X_p are the linear independent or explanatory variables, X_1^2, X_2^2, ..., X_p^2 are their respective squared or quadratic variates, the B_0 to B_{pp} represent the population regression coefficients, and E is the error term that accounts for the remaining unexplained variability in Y. The usual assumptions in the regression analysis were made except that it was recognized that the intercorrelations between the Xs occurred to some extent. The problem of intercorrelation in this sort of data has been discussed by Pena-Olvera (1979). The HELARCTOS II computer program (Kennedy, 1971) was used to compute the regression models.

As a preliminary step, an agronomic selection of the variables contained in the final data set in Appendix Tables A4 and A6 of Sridodo (1980) was performed in order to delete from the study those variables that showed little or no effects in previous research studies. The variables selected for this study are presented in Appendix Table A1. The means and ranges of these variables were then calculated and are given in Appendix Table A4. Thereafter, the development of the model involved the use of the statistical procedures next described.

The correlation analysis consisted of the computation and analysis of simple correlation matrixes of the variables for each leaf nutrient. Previous research by Henao (1976), Pena-Olvera (1979), and Sridodo (1980) showed that, if the correlation between two predictor variables is greater than ± 0.60, one of the two variables should be deleted. If both variables are present in the regression model, a distortion of the regression coefficients will occur. To avoid this problem, the pairs of variables correlated higher than ± 0.60 were evaluated by computing a series of alternative regression models for each leaf nutrient on the linear variates of soil and management variables. The variable giving the higher R^2-value was retained. If some question remained as to which variable to delete, both variables were retained for further evaluation in the next step through the computation of alternative quadratic regression models.

In the model selection steps, an initial quadratic regression model of each leaf nutrient on linear and squared variates of the soil and management variables was fitted by the HELARCTOS II computer program to determine the most significant variates, as well as to further assess the pairs of highly correlated variables still included in the data set. After the complete model was computed, nonsignificant variates were deleted by stepwise, backward elimination. The criteria for retention of a given variate in the model were: (1) from the t-tests applied to the partial regression coefficients of the variates, only those were retained whose probability was less than $\alpha = 0.10$, except that the linear variate was retained regardless of its significance if its squared variate was significant at the 10% level, (2) no variables were to be included with simple correlation coefficients greater than ± 0.60, and (3) after comparing correlated variables in alternative models, the one of the pair giving the higher R^2-value, though only slightly higher, was retained for further computation and the other was deleted.

As a result of these steps, a final quadratic model of each leaf nutrient concentration on selected soil and management variables was obtained. These quadratic base models were used to test the various weather indexes or selected combinations of them.

Testing of the weather indexes

The quadratic base models for each leaf nutrient on selected soil and management variables were used to further test the weather indexes that were selected from the previous correlation analysis. Individual weather indexes or selected combinations of them were added to the base model and were evaluated by the improvement in the R^2-values of the resulting regression models. No highly correlated weather indexes were included in a same model and, at this stage, no interactions between weather indexes and other variables were evaluated. This testing was performed in three stages.

First stage of testing In this stage, the linear and squared variates of the weather indexes computed for the 75-day period from 42 days before to 33 days after the silking date, the 40-day period before leaf sampling date, the 20-day period from 42 days to 22 days before leaf sampling (period A), and the 20-day period from 22 days to 2 days before leaf sampling (period B), as well as the early-season EXMO and PPT46 indexes, were tested in alternative regression models by adding them either individually or in selected combinations to the quadratic base model.

Second stage of testing In this stage, the linear and squared variates of 5-day moisture stress (DV) and precipitation indexes (PPT), as well as those of the 8-day excess moisture and precipitation indexes, were tested by adding them either alone or in selected combinations to the quadratic base model. They were evaluated in terms of the improvement in the R^2-values of the regression models.

To investigate the effects on each leaf nutrient of the individual excess moisture, moisture stress, and precipitation indexes that were computed for continuous intervals of the growing season before the leaf sampling date, the complete regression model including the four types of indexes was reduced by deleting the nonsignificant variates (at the 10% level) of these weather indexes by stepwise, backward elimination.

Third stage of testing After the 5-day DV, PPT, and PPT15 indexes were computed, a summation technique as proposed by Hendricks and Scholl (1943) was applied to these indexes. Summation variates were computed to describe how the rates of change of each leaf nutrient varied across the 40-day period (for the DV and PPT indexes) and the 75-day period (for the PPT15 indexes) before the leaf sampling date. A brief explanation of this technique and how it was applied in this research will be given next.

As was shown in the literature review, the weather-related factors interact among themselves and also influence the effects that soil and management factors have on the plant responses, in addition to the direct effect that they have on the plant processes. The variability of the weather factors throughout the season is another feature that affects these relationships. Hence, there is need to assess the effects of the interactions between weather and soil and management factors on the leaf nutrient concentrations in order to interpret the results of plant analysis.

If various weather indexes are calculated for several intervals of the growing season, the quantitative evaluation of their effects and all of their interactions with other factors on the leaf nutrients seems to be impractical statistically. Fortunately, Fisher (1924) proposed a technique which allows the researcher to estimate the effects of weather factors relative to several intervals of the growing season without unduly increasing the number of independent variables in the regression equation. Hendricks and Scholl (1943) modified Fisher's method in order to estimate the effects of two or more weather factors and their interactions. Leeper et al. (1974) used the same technique to interact seasonal variables (time-independent variables) with weather variables estimated for several time intervals.

Regression analysis has been, as already shown, a common technique for studying the crop-weather relationships. This method consists in fitting to the data an equation of the form,

$$Y = A_0 + A_1X_1 + A_2X_2 + \dots + A_nX_n \quad , \qquad (2)$$

in which Y represents yield of any other plant parameter, X_1 to X_n represent values of n distinct weather factors or values of a weather factor at n different time periods during the growing season, and A_0 to A_n are the regression coefficients.

Fisher (1924) divided the growing season into a number of short intervals in order to measure the effect of precipitation during each interval on the yield of wheat. This was done by fitting equation 2 to the data in which each X variable represented the rainfall in each of the 61 intervals in which he divided the growing season and Y was the final yield. Fisher recognized the theoretical objections to using an equation in which the number of constants to be evaluated is large in relation to the observed data.

If X_1 represents the amount of precipitation for the first interval, X_2 the amount for the second interval, and so on, and each of the corresponding constants A_0 to A_n represents the net effect of an inch of precipitation from the corresponding time interval on the final yield, Fisher then reasoned that the change in the net effect of an inch of precipitation from one interval to the next would not be an abrupt change but an orderly change that could be represented by a mathematical expression. That is, if the numerical values of A_0 to A_n were plotted at equally spaced intervals, they should describe a smooth curve which could be represented by an algebraic expression in which the independent variable is the time interval to which an individual coefficient corresponds.

The form of this algebraic expression is not known but, for the case of an assumed third-order degree polynomial, it is as follows:

$$A_t = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \quad , \tag{3}$$

in which A_t represents the value of any coefficient (A) for any time interval (t). The constants or regression coefficients in equation 2 would then be given by:

$$\begin{aligned} A_1 &= a_0 + 1a_1 + 1^2 a_2 + 1^3 a_3 \quad , \\ A_2 &= a_0 + 2a_1 + 2^2 a_2 + 2^3 a_3 \quad , \\ A_3 &= a_0 + 3a_1 + 3^2 a_2 + 3^3 a_3 \quad , \\ &\vdots \\ A_n &+ a_0 + na_1 + n^2 a_2 + n^3 a_3 \quad . \end{aligned} \tag{4}$$

These equations are obtained from equation 3 by letting t take values 1, 2, 3, ..., n and a_0 to a_3 are the regression coefficients of the cubic relationship between time and the A_0 to A_n coefficients. By substituting these values into equation 2, it can be written as,

$$\begin{aligned} Y = A_0 + a_0&(1X_1 + 1X_2 + 1X_3 + \ldots + 1X) + \\ a_1&(1X_1 + 2X_2 + 3X_3 + \ldots + nX) + \\ a_2&(1^2X_1 + 2^2X_2 + 3^2X_3 + \ldots + n^2X) + \\ a_3&(1^3X_1 + 2^3X_2 + 3^2X_3 + \ldots + n^3X) \quad . \end{aligned} \tag{5}$$

The quantities inside the parentheses can be computed from the precipitation data and interpreted as independent variables. After equation 5 is fitted to the data, the numerical values of a_0, a_1, a_2, and a_3 can be used to compute the numerical values of A_1 to A_n in equation 4. The advantage of fitting equation 3 is that it contains only five constants to be evaluated, whereas the fitting of equation 2 would require the evaluation of as many constants as the number of intervals in the growing season. In fitting equation 3, the number of constants to be evaluated will always be five, regardless of the number of intervals into which the growing season is divided.

One assumption behind this technique is that the effect of a weather factor during any interval in the growing season is independent of any event affecting the crop earlier or later in the growing season. In this respect, Hendricks and Scholl (1943) stated that, as long as the weather conditions at any time are around the mean condition, this restriction probably does not introduce a serious error. A second assumption is that the yield-weather relationship is linear which implies, for instance, that yield increases indefinitely as the amount of precipitation in a given month or time interval increases. Obviously, some optimum value exists beyond which additional precipitation does not increase yield and might even decrease yield. These authors found that this assumption is justified if the weather factors do not fluctuate over too wide a range and added that any curvilinear relationship likely to be present can be represented by a linear function over a short range with a fair degree of accuracy. For this study, this second assumption was replaced by one that a curvilinear (quadratic) relationship exists between the leaf percentages and the weather indexes because the values of the eight 5-day DV, PPT, and PPT15 indexes vary over a wide range. How the quadratic effects were computed will be shown later.

Hendricks and Scholl (1943) also pointed out that some researchers prefer to test a high degree polynomial (fourth or fifth degree), deleting thereafter the nonsignificant terms. However, they indicated that normally a second- or third-order polynomial is adequate since it can be expected that the effect of precipitation, for example, would be small at the beginning of the season, reach a maximum at some time, and perhaps show a decrease until crop maturity is reached.

This summation technique can be applied to study the effects of two or more weather factors, as well as to assess interactions between two weather factors having values for the same time intervals or between a weather factor with interval values and a seasonal variable. How it can be done will be illustrated using the weather indexes estimated in this study.

As was previously shown, the DV and PPT indexes were computed for eight 5-day periods in the period from 42 days to 2 days before leaf sampling date. Also, the fifteen 5-day PPT15 indexes covered a 75-day period from 2 days before leaf sampling back towards the planting date. From here on, the eight 5-day DV and PPT indexes will be referred as the DV_i and PPT_i indexes, where i = 1 to 8. The fifteen 5-day PPT15 indexes will be referred as the PPT15-i indexes, where i = 1 to 15.

The ordinary quadratic regression equation to estimate the linear, quadratic, and interaction effects of the DV_i and PPT_i indexes on LEAFN can be written as:

$$\begin{aligned} LEAFN = {} & A_0 + A_1DV1 + \ldots + A_8DV8 + B_1PPT1 + \ldots + B_8PPT8 + \\ & C_1DV1^2 + \ldots + C_8DV8^2 + D_1PPT1^2 + \ldots + D_8PPT8^2 + \\ & E_1DV1{*}PPT1 + \ldots + E_8DV8{*}PPT8 + \text{base model variates.} \end{aligned} \tag{6}$$

For the application of this summation technique to these data, a third-order degree polynomial was assumed to represent adequately the time effect on the net regression coefficients. In this case, there are five sets of net regression coefficients (regression coefficients in equation 6), namely, the A_1 to A_8 coefficients for the DV_i linear variates, the B_1 to B_8 coefficients for the PPT_8 linear variates, the C_1 to C_8 coefficients for the DV_i squared variates, the D_1 to D_8 coefficients for the PPT_i squared variates, and the E_1 to E_8 coefficients for the $DV_i{*}PPT_i$ interaction variates. These five sets are as follows:

$$\begin{aligned} A_t &= a_0 + a_1t + a_2t^2 + a_3t^3 \quad , \\ B_t &= b_0 + b_1t + b_2t^2 + b_3t^3 \quad , \\ C_t &= c_0 + c_1t \div c_2t^2 + c_3t^3 \quad , \\ D_t &= d_0 + d_1t + d_2t^2 + d_3t^3 \quad , \text{ and} \\ E_t &= e_0 + e_1t + e_2t^2 + e_3t^3 \quad . \end{aligned} \tag{7}$$

By substituting the values of t, the various time intervals (1 to 8, in this case), into equation 7 the following equations result:

$$A_1 = a_0 + 1a_i + 1^2a_2 + 1^3a_3 \quad ,$$

$$A_2 = a_0 + 2a_1 + 2^2a_2 + 2^3a_3 \quad ,$$

$$\vdots$$

$$A_8 = a_0 + 8a_1 + 8^2a_2 + 8^3a_3 \quad ,$$

$$\vdots$$

$$E_1 = e_0 + 1e_1 + 1^2e_2 + 1^3e_3 \quad ,$$

$$E_2 = e_0 + 2e_1 + 2^2e_2 + 2^3e_3 \quad , \text{ and}$$

$$\vdots$$

$$E_8 = e_0 + 8e_1 + 8^2e_2 + 8^3e_3 \quad . \tag{8}$$

If these values are substituted into equation 6, involving 8 time intervals, equation 6 can be written in the form (using nomenclature of Runge and Odell, 1958) as follows:

$$\begin{aligned} \text{LEAF N} = A_0 &+ a_0\Sigma(DV_i) + a_1\Sigma(DV_it_i) + a_2\Sigma(DV_it_i^2) + a_3\Sigma(DV_it_i^3) + \\ &b_0\Sigma(PPT_i) + b_1\Sigma(PPT_it_i) + b_2\Sigma(PPT_it_i^2) + b_3\Sigma(PPT_it_i^3) + \\ &c_0\Sigma(DV_i^{\,2}) + c_1\Sigma(DV_i^{\,2}t_i) + c_2\Sigma(DV_i^2t_i^2) + c_3\Sigma(DV_i^2t_i^3) + \\ &d_0\Sigma(PPT_i^2) + d_1\Sigma(PPT_i^2t_i) + d_2\Sigma(PPT_i^2t_i^2) + \\ &d_3\Sigma(PPT_i^2t_i^3) + e_0\Sigma(DV_i{*}PPT_i) + e_i\Sigma(DV_i{*}PPT_it_i) + \\ &e_2\Sigma(DV_i{*}PPT_it_i^2) + e_3\Sigma(DV_i{*}PPT_it_i^3) + \\ &\text{base model variates,} \end{aligned} \tag{9}$$

where the Σ symbol in the above equation is $\sum_{i=1}^{8}$.

As previously explained, a third-order polynomial includes four variates, namely, the intercept, linear, squared, and cubic variates that describe a curve with two inflection points. As illustrated in equation 9, the intercept summation variate representing the linear functions of the 5-day indexes was obtained by multiplying each 5-day value by the period number (t) to the zero power, and the respective products were summed. These variates were designated as the DVI, PPI, and PPT15I variates. The linear, squared, and cubic summation variates were obtained by multiplying each 5-day value by the period number (t) to the first, second, and third power, respectively, and the resulting products were summed. These variates were designated as the DVL, DVQ, DVC, PPTL, PPTQ, PPTC, PPT15L, PPT15Q, and PPT15C variates, respectively. The abbreviations LDV, LPPT, and LPPT15 were used to briefly represent the four summation variates corresponding to the linear functions of the DV, PPT, and PPT15 indexes, respectively.

The third-order summation variates representing the squared functions of the 5-day indexes were obtained by applying a procedure similar to the one just described to the squared values of each 5-day DV, PPT, and PPT15 index. The four summation variates so obtained were designated as the DVQI, DVQL, DVQQ, DVQC, PPTQI, PPTQL, PPTQQ, PPTQC, PPT15QI, PPT15QL, PPT15QQ, and PPT15QC, respectively. Each set of four variates corresponding to the squared functions of these indexes were briefly represented with the symbols QDV, QPPT, and QPPT15, respectively.

The third-order summation variates corresponding to the interaction effects between the DV and PPT indexes were obtained by applying the same procedure just described to the products of the 5-day DV and PPT indexes corresponding to the same time period. These summation variates were designated as the PPTDVI, PPTDVL, PPTDVQ, and PPTDVC variates. These variates were briefly represented with the IPPTDV symbol. No interactions between the DV and PPT15 indexes were considered because they involved different numbers of intervals.

The interactions involving the 5-day weather indexes and soil and management variables were computed by factoring the respective soil or management variable outside the summation since they were time independent. In this manner, the third-order summation variates representing the effects of these interactions were obtained by multiplying each of the four summation variates representing the linear functions of the 5-day indexes by the value of the soil or management variable of interest. For example, the interaction between the 5-day DV indexes and the variable of NBDCT (applied N other than row N) was computed as follows:

$$f_0 \mathrm{NBDCT}\Sigma(DV_i) + f_1 \mathrm{NBDCT}\Sigma(DV_i t_i) + f_2 \mathrm{NBDCT}\Sigma(DV_i t_i^2) + f_3 \mathrm{NBDCT}\Sigma(DV_i t_i^3) \quad , \tag{10}$$

where the Σ symbol is $\sum_{i=1}^{8}$ and f_0 to f_3 are the regression coefficients associated with these summation variates from which the F_1 to F_8 regression coefficients, that correspond to the interactions between each of the DV1 to DV8 indexes and the NBDCT variable, can be estimated as previously explained.

To ascertain the rate of change of any of the leaf nutrients with respect to any of the weather indexes at any time, t, the regression equation was differentiated with respect to the desired weather index and time interval. For instance, the rate of change of LEAFN with respect to moisture stress can be obtained from equation 9 (plus the third-order summation variates for the DV_i*NBDCT interactions) by taking the partial derivative of LEAFN with respect to the appropriate value of DV_i as follows:

$$\begin{aligned} dLEAFN/dDV_i = {} & (a_0 + a_1t + a_2t^2 + a_3t^3) + \\ & 2(c_0 + c_1t + c_2t^2 + c_3t^3)DV_i + \\ & (e_0 + e_1t + e_2t^2 + e_3t^3)PPT_i + \\ & (f_0 + f_1t + f_2t^2 + f_3t^3)\ NBDCT \quad . \end{aligned} \tag{11}$$

Note that the expressions inside the parentheses are exactly the same as those used to calculate the net regression coefficients of equation 2. It can also be observed that the expression accounting for the quadratic effect of the DV_i in the partial derivative is multipled by a DV_i value that can assume different values depending on the t interval effect being estimated. On the other hand, for the interaction DV_i*NBDCT, NBDCT has a constant value because its value does not vary with time.

Once the summation variates were calculated, they were allotted together with soil and management variables to new data sets in order to assess the different weather indexes or combinations of them. The symbols and identifications of the computed summation variables are presented in Table 3.

To determine the usefulness of this summation technique, a comparison was made of the rates of change of each leaf nutrient with respect to each 5-day DV and PPT index that were calculated from the regression

Table 3. Symbols of the summation variates of a third-order polynomial for the linear, squared, and interaction functions of the 5-day weather indexes

Mathematical expression[a]	Symbols
Linear functions of the 5-day weather indexes (LPPT, LDV, LPPT15)	
$\sum_{i=1}^{n} (X_i t_i^0)$	PPTI, DVI, PPT15I
$\sum_{i=1}^{n} (X_i t_i^1)$	PPTL, DVL, PPT15L
$\sum_{i=1}^{n} (X_i t_i^2)$	PPTQ, DVQ, PPT15Q
$\sum_{i=1}^{n} (X_i t_i^3)$	PPTC, DVC, PPT15C
Squared functions of the 5-day weather indexes (QPPT, QDV, QPP15)	
$\sum_{i=1}^{n} (X_i^2 t_i^0)$	PPTQI, DVQI, PPT15QI
$\sum_{i=1}^{n} (X_i^2 t_i^1)$	PPTQL, DVQL, PPT15QL
$\sum_{i=1}^{n} (X_i^2 t_i^2)$	PPTQQ, DVQQ, PPT15QQ
$\sum_{i=1}^{n} (X_i^2 t_i^3)$	PPTQC, DVQQ, PPT15QC

[a] X represents the 5-day values of PPT, DV, and PPT15 indexes and t,n = 1,2,...,8 for the PPT and DV indexes, and t,n = 1,2,...,15 for the PPT15 indexes.

Table 3. (Continued)

Mathematical expression	Symbols
Interaction functions (IPPTDV)	
$\sum_{i=1}^{n}(PPT_i{*}DV_i t_i^0)$	PPTDVI
$\sum_{i=1}^{n}(PPT_i{*}DV_i t_i^1)$	PPTDVL
$\sum_{i=1}^{n}(PPT_i{*}DV_i t_i^2)$	PPTDVQ
$\sum_{i=1}^{n}(PPT_i{*}DV_i t_i^3)$	PPTDVC

coefficients of the DV_i and PPT_i indexes, when included as independent variables in a regression model, and from the regression coefficients estimated from the third-order summation variates of these indexes that were included in an alternative regression model.

To ascertain if the assumed third-order polynomial was an adequate function to describe the distribution of the rates of change of each leaf nutrient with respect to the 5-day DV, PPT, and PPT15 indexes, a stepwise, backward elimination of the nonsignificant (at the 10% level) summation variates was performed on a regression model that included the third-order summation variates of the linear and squared functions of the DV_i and PPT_i indexes and on a model that included similar summation variates of the DV_i and PPT15-i indexes. From the selection of the weather index variates in this last model, a second base model was obtained which was used to test a number of interactions between the weather indexes and some soil and management variables as well as interactions between variables of the soil and management group, as will be explained next.

<u>Testing of the interactions</u>

The second base model that was obtained from the previous stage, which included selected variates of soil and management variables as well as selected summation variates of the DV and PPT15 indexes and a selected excess moisture index, was used to test a number of interactions between weather indexes and selected soil and management variables. However, to determine the interaction of a weather index with a given soil or management variable, the latter had to be multiplied by each of the summation variates of the weather index. This procedure resulted in a large number of variates included in the model if several interactions were to be evaluated. This problem was handled by building different models which included the variates of the quadratic base model, the variates of the selected weather indexes, plus the number of interaction variates to attain the limit of 100 positions of the HELARCTOS II program.

The full regression model was computed and then reduced by retaining those variates significant at the 10% level. To test additional interactions, a new model was built by filling available spaces left after deletion of the nonsignificant interactions until the 100 positions were completed. This procedure was repeated until no space was available or no additional interactions of agronomic interest were to be tested.

After the testing of interactions between weather indexes and soil and management variables was completed, a similar procedure was applied for the testing of additional variates of selected interactions between variables of the soil and management group. Once this testing was completed, a final selection on all weather, soil, and management variates was performed to delete the nonsignificant variates at the 5% level by stepwise, backward elimination. These reduced models were then the final interaction models for each leaf nutrient. The procedure to interpret the effects of the summation variates of the DV and PPT15 indexes was previously described and the procedure to interpret the effects of the soil and management variables was similar to that described by Sridodo (1980).

RESULTS AND DISCUSSION

The first objective of this study was to assess the effects of weather-related factors, as represented by some weather indexes, and the time of the growing season at which they occur on the corn leaf N, P, and K concentrations at silking time. Because the effects of weather variables on nutrient uptake or nutrient composition are influenced by soil and management variables, as shown in the literature review, the second objective was to determine the combined effects of selected soil, management, and weather variables on the cited nutrient concentrations.

The results of this study will be presented and discussed in three major sections, each corresponding to each of the three leaf nutrients and following the stages outlined in the previous chapter.

Corn Leaf N Concentration

In this section, the relationships between corn leaf N concentration (LEAFN) and weather factors and their variability through the growing season, as well as with some soil and management factors, were investigated.

In a first step, a number of weather indexes that were computed for various periods of the growing season or small subdivisions of some of these periods were preliminarily assessed by means of correlation analysis. In a second step, a base model of LEAFN on selected soil and management variables was developed which was subsequently used to test further some selected weather indexes or selected combinations of them. Lastly, a second base model, which included selected weather indexes and soil and management variables, was utilized to investigate interactions between weather indexes and some soil and management variables as well as some interactions between variables of the soil and management group. Once the final interaction model was obtained, the effects on LEAFN of the selected variables were discussed.

Correlation analysis of weather indexes

The excess moisture, moisture stress, and precipitation indexes were used to relate soil moisture conditions and meteorological factors, as well as their variability through the growing season, to the variability in LEAFN (leaf N concentration).

Initially, the five moisture stress indexes in the soil moisture program and weighted and unweighted precipitation indexes were computed for four periods of the growing season. An excess moisture index and a precipitation index corresponding to the same period (from 3 to 49 days after planting) were also computed. The means and ranges of these indexes are presented in Appendix Table A2. The simple correlation coefficients between the weather indexes within periods are given in Table 4. It was observed that in all periods DT and DW indexes were very highly correlated ($r = 0.98$ to 0.99) and that the DX, DV, and X1 indexes were also very highly correlated ($r = 0.92$ to 0.99). The correlations between DT or DW with DX, DV, and X1 were highest for the 75-day period ($r = 0.86$ to 0.90) and lowest ($r = 0.36$ to 0.43) for the period A (from 42 days to 22 days before leaf sampling).

Table 4. Simple correlation coefficients between moisture stress and precipitation indexes and between these weather indexes and LEAFN for various periods of the growing season[a]

Weather index	Weather index: DX	DW	DV	X1	PPT	PPT..W	LEAFN[b]
75 days, from 42 days before to 33 days after silking date							
DT	.86	.99	.89	.90	.54	.54	.143
DX	-	.85	.98	.97	.49	.49	.190
DW		-	.89	.90	.54	.55	.146
DV			-	.99	.53	.53	.199
X1				-	.53	.53	.200
PPT					-	.91	.148
PPT..W						-	.167
40 days, from 42 days to 2 days before leaf sampling date							
DT	.62	.98	.70	.71	.38	.28	.137
DX	-	.58	.95	.92	.08	.01	.114
DW		-	.69	.71	.43	.35	.150
DV			-	.99	.20	.11	.147
X1				-	.23	.14	.150
PPT					-	.90	.167
PPT..W						-	.194
A (20 days, from 42 to 22 days before sampling date)							
DT	.39	.99	.42	.43	.30	.26	.070
DX	-	.36	.97	.96	-.17	-.17	.026
DW		-	.41	.42	.34	.31	.087
DV			-	.99	-.13	-.14	.063
X1				-	-.11	-.13	.072
PPT					-	.96	.076
PPT..W						-	.087

[a]For n = 1927, r-values of 0.06 and 0.08 are significant at the 5% and 1% levels, respectively.

[b]Correlations between LEAFN and EXMO, LEAFN and PPT46, and EXMO and PPT46 were -0.15, 0.09, and 0.14, respectively.

Table 4. (Continued)

Weather index	DX	DW	DV	X1	PPT	PPT..W	LEAFN
B (20 days, from 22 days to 2 days before sampling date)							
DT	.76	.99	.77	.77	.29	.24	.156
DX	-	.75	.99	.98	.10	.06	.141
DW		-	.76	.77	.33	.28	.155
DV			-	.99	.13	.09	.143
X1				-	.14	.09	.143
PPT					-	.97	.160
PPT..W						-	.170

All five stress indexes were similarly correlated with the precipitation indexes in the 75-day period. In the other three periods, the DT and DW indexes were more correlated with the precipitation indexes within each period (r = 0.29 to 0.43) than were the DX, DV, and X1 indexes (r = -0.17 to 0.23). The two precipitation indexes were very highly correlated (r = 0.90 to 0.97).

The simple correlation coefficients between LEAFN and the weather indexes in the 75-day period (Table 4) were surprisingly high relative to those in the other periods, considering that the 75-day period extended about 33 days after the leaves were sampled. For the 40-day period before leaf sampling, the correlations between LEAFN and the various indexes were somewhat less to somewhat more than those for the 75-day period. All correlations between LEAFN and the weather indexes were very low in the 20-day A period, from 42 days to 22 days before leaf sampling date. The correlations between LEAFN and the precipitation indexes were higher in the 40-day and the 20-day B (from 22 to 2 days before leaf sampling) periods than those with the stress indexes.

These correlations suggest that soil moisture conditions resulting from the weather factors prevailing prior to the time of silking are more associated with LEAFN variability than weather earlier, and that a stress index reflecting those conditions should be as well associated with LEAFN as one computed for the 75-day period.

On the average, the growth stage and the pan evaporation (energy) weighting factors had little effect on the correlations between LEAFN and the moisture stress indexes in the periods prior to leaf sampling date (Table 4). The two-way weighted indexes (DV and X1) had higher correlation coefficients with LEAFN than the one-way weighted or unweighted indexes only in the 75-day period. Weighting of the precipitation indexes by growth stage increased the correlation with LEAFN in all periods. There is no obvious reason to explain these differences in the effects of the weighting factors.

The excess moisture index (EXMO) computed for the 46-day period starting 3 days after planting was negatively correlated with LEAFN ($r = -.15$). However, the precipitation index (PPT46) corresponding to the same period was less and positively correlated with LEAFN ($r = 0.09$).

As a result of the correlation analysis, all indexes for the 20-day A period were omitted from further testing because of their low association with LEAFN. Because of the high correlations between DT and DW indexes and between the DX, DV, and X1 indexes, only the DW and DV indexes were retained from the two groups to evaluate further the effect of the energy weighting factor on the association with LEAFN. The precipitation indexes of PPT75W, PPT40, PPT40W, PPTB, PPTBW, and the early season indexes of EXMO and PPT46 were also retained for subsequent evaluation.

Because weather factors vary through time and space, this variability will have an effect on soil moisture conditions as well as on weather-affected factors which consequently will affect the nutrient uptake and plant processes and hence the nutrient concentration. The indexes already discussed showed that moisture conditions during specific periods can be differentially associated to LEAFN, particularly excess moisture early in the season and moisture stress and rainfall occurring in the 6 weeks prior to leaf sampling. However, these weather indexes were computed over relatively long periods and their variations within the time periods may mask or counteract their effects on LEAFN.

To determine the effects of shorter time periods on the weather-LEAFN relationships, the 40-day period of 42 days to 2 days before leaf sampling was subdivided into eight 5-day intervals and the 5 stress and 2 precipitation indexes were accordingly computed for each interval. The means and ranges of these indexes are listed in Appendix Table A3. Likewise, the 40-day period starting from 3 days after planting was partitioned into six 8-day intervals and the excess moisture and precipitation indexes were computed and accumulated for each interval. Means and ranges of these indexes are also given in Appendix Table A3.

The simple correlation coefficients between LEAFN and the five stress indexes and between the two precipitation indexes for each 5-day period are shown in Table 5. The high correlation between the DT and DW

Table 5. Simple correlation coefficients between LEAFN and the eight 5-day moisture stress and precipitation indexes in the 40-day period before leaf sampling

	Period							
Index	1	2	3	4	5	6	7	8
DT	-.03	.04	.09	.12	.15	.13	.14	.14
DX	-.11	-.01	.11	.09	.11	.06	.09	.16
DW	-.03	.04	.09	.12	.15	.13	.14	.14
DV	-.12	-.01	.11	.09	.11	.05	.09	.16
X1	-.11	.00	.10	.10	.11	.05	.09	.16
PPT	.00	.05	.04	.07	.01	.09	.10	.11
PPTW	.00	.05	.04	.07	.01	.09	.10	.11

indexes was noticeable again since they gave almost identical coefficients within each of the eight 5-day periods. Also, the intercorrelations between the DX, DV, and X1 indexes were revealed by their similar correlations with LEAFN. The same situation was shown by the correlations with both precipitation indexes.

The differential relationships between the soil moisture conditions and LEAFN through the 40-day period were shown by their correlation coefficients in the eight periods. Because of the indicated intercorrelations referred to, only the asociations between LEAFN and the 5-day DV, DT, and PPT indexes will be discussed.

The significant negative correlation between DV1 and LEAFN (r = -0.12) showed that, as DV increased (higher soil moisture), LEAFN decreased, revealing then that a negative effect of excess moisture still occurred at this stage. Loss of available N by denitrification or leaching or poor aeration owing to excess moisture may be causes of this response. This effect was nil in the next 5-day period ($r = -0.01$). From the third period on, an increase in DV (soil moisture) was positively associated with a higher LEAFN level (Table 5). These responses reflect the weather conditions prevailing in Iowa during late June and July when the water balance of the corn crop is negative, that is, water losses by evapotranspiration usually exceed the gains through rainfall leading to greater demand for soil moisture. As a consequence, better soil moisture will favor movement of soil N by mass flow toward the root for increased uptake.

A similar trend is depicted by the correlations involving the eight DT indexes. However, the negative correlation between DT1 and LEAFN is lower ($r = -0.03$) and the positive correlations between DT4 to DT7 and LEAFN are higher than those of the respective DV indexes.

The PPT1 index did not show a negative relationship with LEAFN as the DV1 index did. Precipitation, as an index, does not have a cumulative effect because it only expresses the effects of rainfall in a given period without any relation to the effects of preceding amounts of rain. Therefore, this index may only reveal the effect of a moist soil surface while the cumulative effect is exerted through the DV index. The positive association between LEAFN and PPT2 to PPT8 indexes is due to the effects that rainfall exerts on the soil surface layer which usually is the zone of higher N availability. This effect can be particularly beneficial during July when high evapotranspiration rates dry the soil surface layer more rapidly.

The effects of each 5-day index on LEAFN can be assessed by including each index as an independent variable in a multiple regression equation; this, however, depends on the intercorrelation among these indexes. A high intercorrelation will lead to a distortion of the regression coefficients and will prevent an accurate interpretation of the effects, as indicated by Pena-Olvera (1979).

The simple correlation coefficients between the eight 5-day DT, DV, and PPT indexes are presented in Table 6. Those between the eight DT indexes varied from 0.28 to 0.82. The highest correlation coefficients occurred in or close to the main diagonal which indicates that they are higher between adjacent indexes and decrease gradually with the time between indexes.

The highest correlations between the DV indexes were found also in or near the main diagonal, but their magnitudes were less (r = 0.15 to 0.50) than those between the DT indexes. The correlation coefficients also decreased gradually with the time between indexes. The moderately high correlations between DV6 and DV7 (r = 0.44) and DV7 and DV8 (r = 0.50) should not cause distortion of their regression coefficients if they are included in the same regression model (Henao, 1976).

The correlation coefficients between the eight 5-day PPT indexes were very low (Table 6) and all can also be included in a regression equation to investigate their relationship with LEAFN. Although not presented here, the very low correlations between the eight PPT and the eight DV indexes showed that both types of indexes can be included in the same regression equation with no distortion of their regression coefficients.

Table 6. Simple correlation coefficients between the eight 5-day DT (unweighted), DV (weighted by growth stage and energy), and PPT (unweighted rainfall) indexes

Weather index	r-values for following time periods							
	1	2	3	4	5	6	7	8
DT1	-	.69	.43	.28	.34	.44	.42	.29
DT2		-	.69	.44	.35	.41	.39	.34
DT3			-	.76	.55	.48	.39	.32
DT4				-	.77	.61	.50	.41
DT5					-	.80	.67	.60
DT6						-	.82	.67
DT7							-	.79
DT8								-
DV1	-	.16	.15	.02	.11	.11	-.11	-.03
DV2		-	.24	.27	.04	.09	.10	-.04
DV3			-	.36	.29	.08	.12	.02
DV4				-	.33	.24	.17	.07
DV5					-	.30	.37	.26
DV6						-	.44	.39
DV7							-	.50
DV8								-
PPT1	-	.04	.02	.03	.03	-.01	-.06	-.10
PPT2		-	-.04	.12	.00	.12	-.07	-.02
PPT3			-	-.05	.06	-.04	.06	-.10
PPT4				-	.01	.04	.00	.00
PPT5					-	.00	.04	-.01
PPT6						-	-.02	-.01
PPT7							-	.04
PPT8								-

The simple correlation coefficients between the six 8-day excess moisture indexes (Table 7) revealed similar trends as for the DV indexes. The highest ones were at or near the main diagonal and varied from r = 0.21 (EXMO1 and EXMO2) to r = 0.54 (EXMO5 and EXMO6). The correlations between the four PPTEM indexes were also low and those between the excess moisture and precipitation indexes were low, with a maximum of 0.33 (EXMO5 and PPTEM4).

Although the correlations between the 6 EXMO, the 4 PPTEM, and the 8 DV and PPT indexes are not presented, all were low or very low (maximum r = 0.25) which means that all four indexes can be included in a regression model to characterize the effects on LEAFN of weather factors from planting to leaf sampling.

Finally, the correlation coefficients between LEAFN and the 6 excess moisture indexes and the 4 PPTEM indexes are presented in Table 7. Highest negative correlations were found between EXMO2 to EXMO5 and LEAFN which suggested that excess moisture occurring from about 11 to 43 days after planting caused lower LEAFN levels. Rainfall occurring during the four 8-day periods after planting had little association with LEAFN, although negative correlations between PPTEM3 and PPTEM4 and LEAFN indicated that high rainfall had a negative effect on LEAFN at sampling time.

Although the correlation analysis pointed out some linear relationships between the various weather indexes during the growing season and LEAFN, the four types of indexes, which vary over a wide range, may have curvilinear effects on LEAFN. Besides, simple correlation coefficients only indicate the association between two variables when effects of other

Table 7. Simple correlation coefficients between excess moisture and precipitation indexes for the six 8-day periods following 3 days after planting, and between these indexes and LEAFN

	EXMO2	EXMO3	EXMO4	EXMO5	EXMO6	PPTEM1	PPTEM2	PPTEM3	PPTEM4	LEAFN
EXMO1	.21	.17	.13	.10	.21	.21	.06	-.09	-.02	-.02
EXMO2	-	.41	.30	.25	.21	.18	.25	.09	.00	-.10
EXMO3		-	.45	.35	.28	.01	.17	.26	.18	-.12
EXMO4			-	.54	.42	-.04	.01	.18	.33	-.15
EXMO5				-	.54	-.05	-.04	.09	.29	-.12
EXMO6					-	.00	-.03	.01	.14	-.07
PPTEM1						-	-.04	-.13	-.11	.06
PPTEM2							-	-.01	-.15	.00
PPTEM3								-	.14	-.04
PPTEM4									-	-.07

variables are not considered; hence, only multiple regression analysis can evaluate the relationships between LEAFN and weather, soil, and management variables.

Development of the base regression model

In order to select the weather indexes best related to LEAFN, a base quadratic model of LEAFN on selected soil and management variables was computed following the procedures described in the previous chapter. The variables were described in Table 1 in the preceding chapter and their means and ranges are shown in Appendix Table A4.

Correlation analysis   Simple correlation coefficients between all linear variates were determined at the same time as the initial multiple regression of LEAFN was computed by the HELARCTOS II program. The correlation coefficients between two variables that were greater than ± 0.40 are listed in Table 8. Noticeable in this table is the lack of any relevant correlation between LEAFN and the intended predictor variables. The only important correlation detected was that between LEAFN and LEAFP ($r = 0.57$) which reveals the parallel behavior of these two leaf nutrients so often referred to in the literature. However, LEAFP is not a predictor variable for LEAFN because the chief aim of this study is to understand how the variability in LEAFN is related to the weather, soil, and management factors.

The correlations shown involved basically the same pairs of variables and are of similar magnitude as those reported by Sridodo (1980) and Macias-Laylle (1984). This was expected because the variables for this study were derived from basically the same data set as the one used by

Table 8. Simple correlation coefficients greater than or equal to ±0.40 between variables included in the base model for LEAFN[a]

Between variables	r-values	Between variables	r-values
LEAFN and LEAFP	.57	PH1 and PHMIN	.64
		DCAL	.48
LEAFP and STP1	.41		
		STK1 and STK2	.72
LEAFK and STK1	.63	STP1	.41
STK2	.42		
		EXMO and CMAX	.53
PLDEN and ROWWID	−.45	PALEO	.45
NBDCT	.53		
KBDCT	.44	PAWC and SAND	−.65
HYCROSS	.42	TILL	−.41
PROW and NROW	.85	RANGE and PHMIN	.59
KROW	.76	DCAL	.46
		STK1	.54
KROW and NROW	.59	STK2	.50
PAWC	.40	KROW	−.54
TILL	.51	PLMETH	−.44
		TILLAFT	−.42
NBDCT and PBDCT	.47	PAWC	.45
NBDCT	.46	BIO	.40
NRES1	.46		
NCODE1	.41	EROS and THAHOR	−.87
HYCROSS	.44		
		DRAIN and THAHOR	.44
PBDCT and KBDCT	.62	CPL	.48
KCODE and NCODE1	−.50	CMAX	.62
		TILE	.45
NRES1 and PRES1	.80		
KRES1	.64	CPL and CMAX	.67
STP1	.45	DPHMIN	−.40
NCODE1	.49		
PRES1 and KRES1	.84	STP2 and BIO	−.49
STP1	.43	DPHMIN	.49
		DCAL	−.45
SLOPE and ROWSLP	.49		
EROS	.66	ALLUV and STK2	.55
THAHOR	−.58	DCAL and PHMIN	.72
DRAIN	−.43	DPHMIN	−.41

[a]For n = 1934; LEAFP and LEAFK were not included in the base model for LEAFN.

these workers. Therefore, the interpretation of such correlations will be essentially the same and will not be discussed further.

Alternative regression models of LEAFN on linear functions of the soil and management variables were first run to select from the pairs of highly correlated variables the ones which gave the higher R^2-values. In this manner, the deleted variables from the fertility management group were KBDCT, PRES1, KRES1, and PRES3. The highly correlated row-applied fertilizer variables (NROW, PROW, and KROW) were retained for further evaluation in quadratic models because the linear models gave no clear indication as to which variable to retain.

Likewise, the correlations between PAWC and SAND, EROS and THAHOR, CPL and CMAX, DCAL and PHMIN, and STK1 and STK2 were evaluated by the alternative regressions and the EROS, CMAX, SAND, PHMIN, and STK1 variables were deleted. From the environmental group, the RL3 (because of nonsignificance) and the SL1 and CB2 variables were deleted. Because the SL1 and CB2 variables represent occurrences after the time of leaf sampling, their relationships with LEAFN probably are meaningless. Although the regression coefficients for these two variables were significant in the linear model, their effects may be through an unknown indirect relationship.

Model selection A series of multiple regression models of LEAFN on linear and quadratic functions of selected variables were computed in order to determine the most significant terms and to further evaluate the highly correlated variables still retained. These quadratic models were identified as the Model LEAFN-A series and the variates included are listed in Table 9. A total of 48 linear variates along with 42 quadratic functions were investigated in this series.

The stepwise, backward selection procedure performed was explained by Sridodo (1980) and was generally outlined in the previous chapter. The model selection steps for the Model LEAFN-A series are shown in Table 10.

The complete quadratic model of LEAFN on 90 variates had an R^2 of 0.399. Deletion of 40 variates in 7 steps caused little reduction of the R^2 of Model LEAFN-A8 (Table 10). After deletion of their squared variates, the linear terms of CRW, CULT, ROWWID, TILE, PRES2, ROWSLP, PAWC, NRES1, and DRAIN showed nonsignificant effects on LEAFN and were also deleted without a noticeable effect on the R^2-value.

Models LEAFN-A4 to -A7 were also utilized to determine which of the highly correlated row-applied fertilizer variables to retain. In this manner, the variates for the NROW and PROW variables were deleted and the KROW variable was retained. The significant negative linear and positive squared KROW variates indicated that row-applied K decreased LEAFN at a decreasing rate. This negative effect of K fertilizer on LEAFN has been reported by Powell (1968), Voss (1969), and Miranda (1981) from their analyses of fertilizer experiments conducted in Iowa.

Models LEAFN-A1 to -A8 still contained the linear and squared variates of the DV75 ane EXMO weather indexes. Because this base model was developed to evaluate the various weather indexes computed, those variates were deleted in Model LEAFN-A9, which decreased the R^2 from 0.394 to 0.370.

Table 9. Variates included in the base regression Model LEAFN-A series

X_i[a]	Variate	X_i	Variate	X_i	Variate
2	LEAFN	39	TWP	73	$TILE^2$
6	PLDEN	40	RANGE	74	$NRES1^2$
7	BARR	41	THAHOR	75	$PRES2^2$
8	CRW	42	DRAIN	76	$SLOPE^2$
9	CB1	43	CPL	77	$ROWSLP^2$
10	WEEDS	44	DCMAX	78	$PH1^2$
11	CULT	45	BIO	79	STN^2
12	PLOW	46	LOESS/T	80	$STP1^2$
13	TILLAFT	47	TILL	81	$STK1^2$
14	PLDATE	48	PALEO	82	$DV75^2$
				83	$EXMO^2$
16	PLMETH	49	COLLUV		
17	ROWWID	50	ALLUV	84	$PAWC^2$
18	MANURE	51	DPHMIN	85	$NCODE1^2$
19	NROW	52	DCAL	86	$HYMAT^2$
20	PROW	53	STP2	87	$HYCROSS^2$
21	KROW	54	SAMDIF	88	TWP^2
22	NBDCT			89	$RANGE^2$
23	PBDCT	57	$PLDEN^2$	90	$THAHOR^2$
24	TILE	58	$BARR^2$	91	$DRAIN^2$
25	NRES1	59	CRW^2	92	CPL^2
26	PRES2	60	$CB1^2$	93	$DCMAX^2$
27	SLOPE	61	$WEEDS^2$	94	BIO^2
28	ROWSLP	62	$CULT^2$	95	$DPHMIN^2$
29	PH1	63	$PLOW^2$	96	$DCAL^2$
30	STN	64	$TILLAFT^2$	97	$STP2^2$
31	STP1	65	$PLDATE^2$	98	$SAMDIF^2$
32	STK1	66	$ROWWID^2$		
33	DV75	67	$MANURE^2$		
34	EXMO	68	$NROW^2$		
35	PAWC	69	$PROW^2$		
36	NCODE1	70	$KROW^2$		
37	HYMAT	71	$NBDCT^2$		
38	HYCROSS	72	$PBDCT^2$		

[a]This number indicates the order of the variate in the data set arranged to compute the base model.

Table 10. Model selection steps to derive the base model for LEAFN, Model LEAFN-A series

Model no.	No. of variates	Identification	R^2
LEAFN-A1	90	Complete model, all variates listed in Table 9	.399
A2	80	Deleted $PLDATE^2$, $MANURE^2$, $PBDCT^2$, $TILE^2$, $PRES2^2$, $SLOPE^2$, $ROWSLP^2$, $STK1^2$, $PAWC^2$, and $DRAIN^2$	.399
A3	71	Deleted $WEEDS^2$, $ROWWID^2$, $NRES1^2$, $PH1^2$ $HYMAT^2$, TWP^2, $DCMAX^2$, $DCAL^2$, and STP^2	.398
A4	60	Deleted CRW^2, $CULT^2$, $PLOW^2$, $PROW^2$, ROWWID, TIL, PRES2, ROWSLP, DRAIN, LOESS/T, and COLLUV	.397
A5	57	Deleted $NROW^2$, CRW, and PROW	.397
A6	55	Deleted $THAHOR^2$ and $DPHMIN^2$	.396
A7	52	Deleted NROW and PAWC	.395
A8	50	Deleted CULT and NRES1	.394
A9	46	Deleted DV75, $DV75^2$, EXMO, and $EXMO^2$ from Model LEAFN-A8	.370
A10	44	Deleted BARR and $BARR^2$ from Model LEAFN-A9	.269

Likewise, all models in this series still had the linear and squared variates of the BARR variable. Aldrich et al. (1975) stated that barren plants were related to low fertility, drought, excessive plant density, insect damage to the roots, stalks, or emerging silks, poor timing of silking and pollen shed, and varietal differences. Lang et al. (1956) observed that barrenness was affected more by plant density than by hybrid or soil fertility. It seems, then, that this variable integrates the effects of several environmental factors as well as those of their interactions on yield and, in this case, on LEAFN. As for prediction purposes, Henao (1976) deemed that, although the elimination of this variable reduced the R^2 about 0.18, it was not a useful predictor of yield for the general population and that its presence in the model could alter the effects of other variables.

The effects of the BARR variable can be related to weather factors and their interactions with soil and management factors. By retaining the BARR variable in the model, the effects of the weather indexes as well as those of the soil and management factors could be contrasted in its absence or presence and, to a certain extent, an idea might be obtained of how the effects of the BARR variable are related to weather factors. The deletion of the BARR variates reduced the R^2 from 0.370 to 0.269 in Model LEAFN-A10 (Table 10).

Model LEAFN-A9 will then be used as the base model to compare the effects of the various weather indexes on LEAFN in the presence of selected soil and management variables. Later, the BARR variable will be deleted to ascertain its possible relationship with the weather indexes.

The regression statistics of Model LEAFN-A9 on selected soil and management variates are given in Table 11. The regression coefficients of most of the variates included were significant at either the 1%, 5%, or 10% levels. Linear variates of HYMAT, STP2, THAHOR, and TWP were kept for evaluation in later models. Model LEAFN-A9 was computed to compare the effects of the weather indexes; therefore, no attempt will be made to discuss the effects on LEAFN of the variables herein selected.

Testing of the weather indexes

Model LEAFN-A9 was used as the base model to assess the weather indexes that were selected for further testing by the correlation analysis. Individual weather indexes or combinations of them were added to the base model and evaluated in the resulting regression models by the improvement in the R^2-values. Care was taken to prevent the inclusion of highly correlated indexes in the same regression model.

In the first stage of this testing, the moisture stress and precipitation indexes that were computed for the 75-day period, the 40-day period before sampling, and the period from 22 days to 2 days before leaf sampling, as well as the EXMO and PPT46 indexes, were evaluated in alternative regression models.

In the second stage, the moisture stress (DV) and precipitation indexes (PPT) computed for the eight 5-day periods in the 40-day period before the leaf sampling date were evaluated by including one or both types of indexes in alternative regressions. Likewise, the six 8-day excess moisture indexes (EXMO1 to EXMO6) and the four 8-day precipitation indexes (PPTEM1 to PPTEM4) computed for the period commencing 3 days after

Table 11. Regression statistics of the base model of LEAFN on selected variates, Model LEAFN-A9[a]

Variable	b_i Linear	b_i Squared	Variable	b_i Linear	b_i Squared
BARR	-0.00330**	0.000587**	STP1	0.00113	-0.00000600
CB1	0.00699*	-0.000285*	STK1	0.000214**	-
WEEDS	-0.000283**	-	STP1	-0.000861	-
PLDEN	-0.00192**	0.00000178**	THAHOR	-0.000635	-
PLOW	-0.0526**	-	CPL	0.0150**	-0.000349**
TILLAFT	0.0249++	-0.00340*	DCMAX	0.000610*	-
PLDATE	0.00224*	-	BIO	0.0968*	-0.0124*
PLMETH	0.0372*	-			
HYMAT	-0.0113	-	TILL	-0.0470*	-
HYCROSS	-0.162**	0.0303**	PALEO	-0.170**	-
			ALLUV	-0.0694**	-
MANURE	0.00138*	-			
KROW	-0.00581**	0.0000861**	DPHMIN	0.00100*	-
NBDCT	0.00263**	-0.00000328*	DCAL	-0.000394++	-
PBDCT	-0.00144**	-			
NCODE1	-0.0204**	0.000319**	TWP	0.00149	-
			RANGE	-0.00474++	0.000114*
PH1	-0.00246*	-			
STN	0.0145**	-0.0000892**	SAMDIF	0.00914*	-0.00581**

[a]Intercept = 2.864 and R^2 = 0.370, no. of variates = 46, and no. of observations = 1934.

**,*,++Significant at the 1%, 5%, and 10% levels, respectively, in this and all subsequent tables.

planting were assessed either individually, combined, or in combination with the stress and precipitation indexes.

The third stage dealt with the testing of the summation variates of the eight 5-day PPT and DV indexes calculated by the technique of Hendricks and Scholl (1943). The summation variates of each index were also tested either individually or combined with those of the other index and with or without the EXMO, EXMO12, EXMO34, EXMO56, and PPTEM1 to PPTEM4 indexes. Only those combinations that allowed for comparisons of the effects of the various weather indexes were used.

First stage of testing The first step of this stage of testing was to determine the simple correlations between the weather indexes, as shown in Table 12. This was done to determine which combinations of weather indexes could be evaluated without distortion problems because of high intercorrelations.

As shown in Table 12, the DV and DW indexes, as well as the PPT indexes, were highly intercorrelated within and among the three periods. The moisture stress and precipitation indexes showed high correlations in the 75-day period while their correlations in the other two periods were rather low. The EXMO index was little correlated with the others, but the PPT46 index was highly correlated with the PPT40 index and moderately correlated with most of the others. In all periods, correlations between the DV indexes and PPT46 were lower than those between the DW indexes and PPT46.

One can conclude from this correlation analysis that one of the two moisture stress indexes (DV or DW types) and the weighted or unweighted

Table 12. Simple correlation coefficients ≥ 0.40 between various weather indexes computed for different periods of the growing season

Weather index	r-values for the following											
	DW75	PPT75W	DV40	DW40	PPT40	PPT40W	DVB	DWB	PPTB	PPTBW	EXMO	PPT46
DV75	.89	.53	.74	.76	.47	.45	.77	.77	-	-	-	.46
DW75	-	.55	.49	.83	.50	.49	.59	.84	.41	-	-	.49
PPT75W		-	-	-	.66	.73	-	-	.62	.63	-	.46
DV40			-	.69	-	-	.93	.67	-	-	-	-
DW40				-	.43	-	.75	.98	-	-	-	.48
PPT40					-	.90	-	.46	.68	.63	-	.79
PPT40W						-	-	.40	.86	.88	-	.65
DVB							-	.76	-	-	-	-
DWB								-	-	-	-	.48
PPTB									-	.97	-	.46
PPTBW										-	-	.40
EXMO											-	-

precipitation index for one of the two periods before leaf sampling date can be combined with either the EXMO or the PPT46 index, except that PPT40 and PPT40W cannot be combined with PPT46. A combination of weather indexes could then estimate the effects on LEAFN of weather conditions occurring in the period from 3 days after planting to leaf sampling date.

A series of alternative regression models were then computed, first, to compare different weather indexes and, second, to test some rational combinations of them. These were designated the Model LEAFN-B series; the models included and their respective R^2-values are given in Table 13. Linear and squared variates of the tested weather indexes were included in each model along with the variates in the base model.

Models LEAFN-B1 to LEAFN-B4 were run to assess the individual and combined effects of EXMO and DV75 on LEAFN. Addition of the EXMO variates improved the R^2 very little, more improvement was attained with the DV75 index, and an almost additive effect on the R^2 was noticed by including both indexes (Table 13). Models LEAFN-B4 and LEAFN-B5 showed that more variability was explained by using DV75 (weighted by both energy and growth stage) than DW75 (weighted by growth stage). However, total precipitation for the 75-day period (PPT75W) and the EXMO index gave a similar R^2 as was obtained by using the elaborate moisture stress index.

Models LEAFN-B7 to -B10 included comparisons of the indexes for the 40-day period before leaf sampling. The DW40 and the DV40 indexes gave similar R^2-values, indicating no effect of the energy weighting factor.

Table 13. R^2-values of the alternative regressions of LEAFN on the base model and selected weather indexes, Model LEAFN-B series

Model no.	Variables	R^2
LEAFN-B1	Base model[a]	.370
B2	Base model + EXMO[b]	.376
B3	+ DV75	.387
B4	+ EXMO + DV75	.394
B5	+ EXMO + DW75	.386
B6	+ EXMO + PPT75W	.390
B7	+ EXMO + DV40	.392
B8	+ EXMO + DW40	.392
B9	+ EXMO + PPT40	.411
B10	+ EXMO + PPT40W	.405
B11	+ EXMO + DVB	.392
B12	+ EXMO + DWB	.393
B13	+ EXMO + PPTB	.393
B14	+ EXMO + PPTBW	.392
B15	+ PPT46 + DV75	.396
B16	+ PPT46 + DW75	.389
B17	+ PPT46 + DV40	.393
B18	+ PPT46 + DVB	.393
B19	+ EXMO + DV40 + PPT40	.416
B20	+ EXMO + DVB + PPT40	.415
B21	+ EXMO + DVB + PPTB	.405
B22	+ PPT46 + DVB + PPTB	.405
B23	+ EXMO + PPT46 + DVB + PPTB	.410

[a]The base model was Model LEAFN-A9 (Table 11) with 46 variates and R^2 of 0.370.

[b]The models included quadratic functions of the weather indexes.

The rainfall amount for this period gave the highest R^2 (0.411) and was even higher than that obtained with the weighted precipitation index. These findings suggested that the variability in LEAFN was more related to the amount of rainfall in the 40-day period before leaf sampling than to the soil moisture stress occurring in the same period.

The R^2-values of the remaining models in Table 13 showed that no further improvement occurred except in Models LEAFN-B19 and -B20 in which DV40 or DVB was included along with EXMO and PPT40 (R^2 = 0.416 and 0.415, respectively). No improvement in the R^2 was observed by using the PPT46 index instead of the EXMO index. Models including the DV75, DV40, or DVB indexes (along with the EXMO index) gave similar R^2-values; this suggested that the moisture stress conditions occurring in the 20-day B period accounted for the same variability of LEAFN as moisture stress conditions over longer periods.

The t-values (not presented here) of the regression coefficients showed that the EXMO index had a highly significant linear negative effect on LEAFN, PPT40 had highly significant linear (positive) and squared (negative) effects on LEAFN, while both coefficients of the DV40 or DVB indexes were not significant. Evidently, PPT40 had the dominant effect on LEAFN in this series.

<u>Second stage of testing</u> Next, the eight 5-day DV and PPT indexes in the 40-day period before leaf sampling were evaluated in alternative regression models, either individually or combined with other indexes. In the same series, the six 8-day excess moisture indexes and the four 8-day PPTEM indexes were also tested. Models computed in this stage were

designated as the Model LEAFN-C series. Table 14 presents the weather indexes that were included in the alternative regression models as well as their respective R^2-values.

Alternative Models LEAFN-C1 to -C5 were computed to ascertain the effects of the 5-day PPT and DV indexes on LEAFN and on the R^2-values (Table 14). The addition of the squared variates of each index had a slight effect on the R^2-values. There was no difference between the R^2-values obtained with the PPT or DV indexes. However, a combination of the quadratic functions of both in Model LEAFN-C5 increased the R^2 about 0.036 (3.6%) as compared to the R^2 of models containing only one of these indexes. In this case, the PPT and DV indexes exerted a complementary effect on explaining the variability on LEAFN; previously, when the PPT40 and the DV40 indexes were combined (Table 13), the R^2 was increased only slightly by the combination.

Addition of the linear variate of the EXMO index (its squared variate was not significant in other models) to Model LEAFN-C6 gave only a very small increase in the R^2. However, the t-value of its regression coefficient indicated a highly significant negative effect on LEAFN. When EXMO was added, the regression coefficients of the PPT and DV variates decreased slightly indicating that, in the absence of EXMO index, the other indexes explained its effects to a certain extent due to the intercorrelations among them.

Addition of the six excess moisture indexes (EXMO1 to EXMO6) and the early-season PPTEM indexes (PTEM1 to PTEM4) either alone or in combination had less effect on the R^2-values than the 5-day PPT and DV indexes (Models

Table 14. R^2-values of the alternative regressions of LEAFN on the base model and selected weather indexes, Model LEAFN-C series

Model no.	Variables (base model plus following weather variables)[a]	No. of weather variates	R^2
LEAFN-C1	PPT1 to PPT8 (linear variates, only)	8	.394
C2	PPT1 to PPT8	16	.408
C3	DV1 to DV8 (linear variates, only)	8	.400
C4	DV1 to DV8	16	.410
C5	PPT1 to PPT8 + DV1 to DV8	32	.446
C6	PPT1 to PPT8 + DV1 to DV8 + EXMO[b]	33	.450
C7	PPTEM1 to PPTEM4	8	.378
C8	EXMO1 to EXMO6	12	.388
C9	PPTEM1 to PPTEM4 + EXMO1 to EXMO6	20	.392
C10	PPT1 to PPT8 + PPTEM1 to PPTEM4	24	.413
C11	PPT1 to PPT8 + EXMO1 to EXMO6	28	.421
C12	PPT1 to PPT8 + PPTEM1 to PPTEM4 + EXMO1 to EXMO6	36	.424
C13	DV1 to DV8 + PPTEM1 to PPTEM4	24	.426
C14	DV1 to DV8 + EXMO1 to EXMO6	28	.431
C15	DV1 to DV8 + PPTEM1 to PPTEM4 + EXMO1 to EXMO6	36	.437
C16	PPT1 to PPT8 + DV1 to DV8 + PPTEM1 to PPTEM4	40	.453
C17	PPT1 to PPT8 + DV1 to DV8 + EXMO1 to EXMO6	44	.459
C18	PPT1 to PPT8 + DV1 to DV8 + PPTEM1 to PPTEM4 + EXMO1 to EXMO6	52	.462
C19	Reduced model, deleted nonsignificant variates from Model LEAFN-C18	24	.454
C20	Reduced model, deleted BARR and $BARR^2$ and then nonsignificant variates from Model LEAFN-C18	29	.389
C21	Deleted BARR and $BARR^2$ from Model LEAFN-C6	33	.381

[a]Except where indicated, models included quadratic functions of the weather indexes; base model was Model LEAFN-A9 (Table 11) with 46 variates and R^2 of 0.370.

[b]$EXMO^2$ was not included in this model.

LEAFN-C7 to -C9, Table 14). Both early-season indexes, however, gave slight, additive increases in the R^2-values when added to the combinations of the 5-day PPT and DV indexes (Models LEAFN-C10 to -C18, Table 14). In the presence of the early-season indexes, the DV indexes gave R^2-values about 1% larger than those of models with the PPT indexes (pairwise comparisons, Models LEAFN-C10 to -C15, Table 14).

During the first stage of this testing, the PPT indexes gave higher R^2 than the DV indexes; however, if partitioned into shorter time periods, the DV indexes gave higher R^2-values. These effects suggested that, if the DV index is computed for relatively long periods, it may include opposite effects which decrease the association of the overall index with the intended dependent variable. When partitioned into shorter time periods, the differential effects of moisture stress during the growing season then can be identified and the general relationship can be improved. Partitioning of the precipitation into several shorter time periods did not improve its relationship with LEAFN; the effects of the partitioned precipitation indexes on LEAFN, therefore, were probably in the same direction across the 40-day period.

No reference has been made up to this point to the individual effects on LEAFN of the various partitioned weather indexes. The computed models were not reduced by deleting nonsignificant variates of these indexes because they were calculated for contrasting the general effects of the indexes on the explained variability on LEAFN.

To determine the relative importance of excess moisture, moisture stress, and precipitation indexes, as computated for continuous intervals of the growing season before leaf sampling date, complete Model LEAFN-C18 was reduced by deleting the nonsignificant variates at the 10% level by stepwise, backward elimination. This model was chosen because it included the effects of the weather variables on LEAFN throughout the period from 3 days after planting to 2 days before leaf sampling. Reduced Model LEAFN-C19 was obtained from this selection and the regression statistics of the significant weather indexes are given in Table 15.

Inspection of Model LEAFN-C19 revealed that excess moisture conditions occurring from about 19 days to 43 days after planting had negative effects on LEAFN, as indicated by the regression coefficients of the EXMO3, EXMO4, and EXMO5 indexes. Only the EXMO3 index had a curvilinear effect on LEAFN. On the other hand, only the rainfall occurring in the fourth 8-day period (PPTEM4 index) had a significant, negative effect on LEAFN.

As the DV1 index increased (higher soil moisture), the LEAFN decreased at a decreasing rate (Table 15) and reached a minimum at DV1 = 0.20, at the upper range of observed values (Appendix Table A3). The DV2 index had no significant effect on LEAFN and the DV3, DV4, and DV5 indexes increased LEAFN at decreasing rates up to DV values greater than their means and then they decreased LEAFN. The DV effects on LEAFN in the middle of the 40-day period prior to leaf sampling changed from positive to negative as the situation changed from moisture stress to excess moisture, as shown by these curvilinear responses.

A different effect was observed in the response of LEAFN to the DV8 index. Its regression coefficients showed that, as DV8 increased (from severe to less moisture stress), the LEAFN decreased at a decreasing rate

Table 15. Regression statistics of the selected weather indexes in reduced Models LEAFN-C19 and LEAFN-C20

	Model LEAFN-C19[a]			Model LEAFN-C20[b]		
	bi			bi		
Variable	Linear	Squared	Quadratic effect[c]	Linear	Squared	Quadratic effect[c]
EXMO2	-	-	-	-0.0276*	-	-
EXMO3	-0.0789**	0.0252**	MIN at 1.56	-0.0725**	0.0243**	MIN at 1.49
EXMO4	-0.0345*	-	-	-0.0368*	-	-
EXMO5	-0.0314++	-	-	-0.0396++	-	-
EXMO6	-	-	-	0.0653++	-	-
PPTEM1	-	-	-	0.0100*	-	-
PPTEM2	-	-	-	-0.0119	0.00412++	MIN at 1.45
PPTEM4	-0.0122**	-	-	-0.0109*	-	-
PPT3	0.0387**	-0.00629*	MAX at 3.08	0.0431**	-0.00640++	MAX at 3.37
PPT4	0.0286**	-	-	0.0266**	-	-
PPT5	0.0370**	-0.0106**	MAX at 1.75	0.0431**	-0.0111**	MAX at 1.93
PPT6	0.0189**	-	-	0.0255**	-	-
PPT7	0.0601**	-0.00873**	MAX at 3.44	0.0704**	-0.00952**	MAX at 3.70
PPT8	0.0191**	-	-	0.0527**	-0.00638*	MAX at 4.13
DV1	-3.789**	9.445*	MIN at 0.20	-4.315**	10.375*	MIN at 0.21
DV3	1.981*	-2.893++	MAX at 0.34	2.525**	-4.063*	MAX at 0.31
DV4	2.795**	-5.082**	MAX at 0.27	3.087**	-5.941**	MAX at 0.26
DV5	1.496*	-2.646++	MAX at 0.28	1.662*	-3.047++	MAX at 0.27
DV8	-0.601*	0.932**	MIN at 0.32	0.0270**	-	-

[a]Intercept = 2.325 and R^2 of 0.454.

[b]Intercept = 2.139 and R^2 of 0.389.

[c]Value of the weather index associated with minimum (MIN) or maximum (MAX) LEAFN; means and ranges of weather indexes are given in Appendix Table A3.

to a minimum at a DV8 value less than its mean and then LEAFN increased at higher DV8 levels. This was not a logical response at the low DV8 level, because the water balance around silking time, under Iowa's conditions, is frequently negative because evapotranspiration exceeds precipitation. Therefore, the LEAFN was expected to be positively related to decreasing moisture stress from severe to moderate moisture stress at this stage of growth. However, higher levels of DV8 did not account for any excess moisture effects as DV3 to DV5 did.

The PPT3 to PPT8 indexes in reduced Model LEAFN-C19 had generally positive effects on LEAFN (Table 15). Only PPT3, PPT5, and PPT7 showed curvilinear effects on LEAFN. They increased LEAFN at a decreasing rate up to a maximum LEAFN; high PPT levels then decreased LEAFN. The positive effects of rainfall during this period can be explained by the fact that adequate rainfall favors the N uptake by keeping moist the upper soil layer in which highest levels of available soil N and other nutrients occur. The negative effects of high rainfall are due primarily to leaching of N beyond the root zone.

Reduced Model LEAFN-C19 still contained the linear and squared variates of the BARR (barren stalk) variable. To estimate how BARR affected the LEAFN responses to the weather indexes, the BARR variates and then nonsignificant variates were deleted from Model LEAFN-C18 and Model LEAFN-C20 (Table 15) was obtained. The deletion of the BARR variable had little effect on the significances and magnitudes of most of the weather index variates that were retained in both Models LEAFN-C19 and -C20. The effect of the PPT8 index on LEAFN changed from positive and linear in

Model LEAFN-C19 to curvilinear but positive in most of its relevant range in Model LEAFN-C20. The effect of DV8 on LEAFN in the absence of the BARR variable became positive and linear which was the expected response. It indicated that higher DV8 (higher soil moisture levels) just before leaf sampling time increased LEAFN linearly. In Model LEAFN-C19, DV8 had a negative effect on LEAFN at severe to moderately severe moisture stress but had a positive effect at higher soil moisture.

The most noticeable change due to deletion of the BARR variable was the retention of additional early-season excess moisture and precipitation indexes (Table 15). However, none of these retained had a highly significant effect on LEAFN. The EXMO2 to EXMO5 indexes in Model LEAFN-C20 indicated that excess moisture had a negative effect on LEAFN from about 11 days to 43 days after planting. However, the EXMO6 index had a weak positive effect on LEAFN similar in direction to that shown by the third and subsequent PPT and DV indexes. On the other hand, the PPTEM1 index had an unexpected linear, positive effect on LEAFN because high soil moisture early in the season generally has had negative effects on LEAFN. The PPTEM2 index had a weak curvilinear effect on LEAFN and PPTEM4 decreased it linearly.

To investigate these changes, the simple correlation coefficients between BARR and the 5-day PPT and DV indexes and the 8-day EXMO and PPTEM indexes were inspected. None of the simple correlation coefficients between BARR and these indexes was greater than -0.17, which is relatively low, hence suggesting that intercorrelation is not an important problem. However, that intercorrelation was indeed present between the BARR variable and these indexes was indicated by the changes in signs, magnitudes, and significances of the regression coefficients.

After deleting the BARR variable, the R^2 decreased from 0.454 in Model LEAFN-C19 (reduced model with BARR variates) to 0.389 in Model LEAFN-C20 (reduced model without BARR variates). However, the use of 29 weather variates in Model LEAFN-C20 improved the R^2 by about 12% as compared to the base model without the BARR variates (Model LEAFN-A10, Table 10). The difference in R^2 between Model LEAFN-A10 and Model LEAFN-A9 (base model with BARR variates) was about 10% and this difference was almost the same as the one between Models LEAFN-A9 and LEAFN-C20. These comparisons show that the weather indexes included in the latter model accounted for about the same variability in LEAFN that the complex BARR variable did.

Third stage of testing After the 5-day PPT and DV indexes were computed, Fisher's summation technique, as modified by Hendricks and Scholl (1943), was applied to these indexes to compute the summation variates (intercept, linear, quadratic, and cubic coefficients) corresponding to a third-order polynomial that describes the variations of the responses of LEAFN to each 5-day index across the 40-day period before the leaf sampling date. The eight summation variates for this order polynomial, four representing the linear and four representing the squared functions of these indexes, were calculated as well as the four summation variates to account for the interaction effects between the PPT and DV indexes. Equation 9 in the previous chapter expressed mathematically how each summation variate was calculated and a description of the symbols used to represent them was given in Table 3.

Once the summation variates were calculated, they were allotted to a new data set along with the variates included in the base model for LEAFN. Because the BARR variable affected the responses to the weather indexes, this variable was not included in this new data set. Each of these summation variates was treated as an independent variable in the alternative regression models that were also computed by the HELARCTOS II program.

To account for the precipitation effects on LEAFN throughout the period from before emergence to leaf sampling, seven additional 5-day precipitation indexes were added to the eight already existent. These 15 indexes were also reduced to eight summation variates (for a third-order polynomial) representing their linear and squared functions. However, no interactions between these precipitation indexes and the 5-day DV indexes were included because the number of intervals for each type of index was different. Henceforth, the fifteen 5-day precipitation indexes will be referred to as the PPT15 indexes to differentiate them from the eight 5-day precipitation indexes (PPT indexes).

In the third stage of this testing, these summation variates were evaluated by adding sets of them either individually or combined to the base model. This testing was carried out to determine the usefulness of the summation technique. If the models including the summation variates yield results comparable to those including the variates of the individual indexes, then these summation variates can be used to investigate how LEAFN is affected by the interactions between the precipitation and moisture stress indexes and some soil and management variables as was explained in the previous chapter.

The six 8-day excess moisture indexes were combined into three indexes because previous modeling had shown that EXMO1, EXMO2, EXMO5, and EXMO6 had nonsignificant effects on LEAFN while EXMO3 and EXMO4 did. In this way, the new indexes EXMO12, EXMO34, and EXMO56 represent sums of two consecutive 8-day excess moisture indexes. Also, the four 8-day PPTEM indexes were included in this testing. Both early-season excess moisture and precipitation indexes were included as quadratic functions in the alternative models.

A summary of the alternative regression models computed for this testing is given in Table 16. These are designated as the Model LEAFN-D series; the symbols of the variables are described in Table 3.

Including the four summation variates representing the squared functions of the PPT and DV indexes improved the R^2 by 0.014 (1.4%) and 0.005 (0.5%) for the PPT and DV indexes, respectively (Models LEAFN-D1, -D2, -D4, and -D5, Table 16). Addition of the 3 excess moisture and the 4 PPTEM indexes increased the R^2 by 1.3% in Model LEAFN-D3 with the PPT indexes and by 2.8% in Model LEAFN-D6 with the DV indexes.

The combined summation variates for the linear and squared functions of both the PPT and DV indexes in Model LEAFN-D7 increased the R^2 from 4.1% to 4.9% above those for either index alone (Table 16). Thus, a reasonable increase in the R^2 was observed by combining both indexes, as was also noticed during the previous stage of this testing. Other effects shown by the alternative models in Table 16 are that the inter-

Table 16. R^2-values of the alternative regression models of LEAFN on the summation variates of a third-order polynomial of the 5-day DV, PPT, and PPT15 indexes and other indexes, Model LEAFN-D series

Model no.	Variables (base model plus following weather variables)[a]	No. of weather variates	R^2
LEAFN-D1	LPPT[b]	4	.312
D2	LPPT + QPPT	8	.326
D3	LPPT + QPPT + PPTEM1 to PPTEM4 + EXMO12 to EXMO56	22	.339
D4	LDV	4	.313
D5	LDV + QDV	8	.318
D6	LDV + QDV + PPTEM1 to PPTEM4 + EXMO12 to EXMO56	22	.346
D7	LPPT + QPPT + LDV + QDV	16	.367
D8	LPPT + QPPT + LDV + QDV + EXMO	18	.372
D9	LPPT + QPPT + LDV + QDV + IPPTDV + EXMO	22	.374
D10	LPPT + QPPT + LDV + QDV + IPPTDV + PPTEM1 to PPTEM4 + EXMO12 to EXMO56	34	.384
D11	LPPT15 + QPPT15	8	.327
D12	LPPT15 + QPPT15 + LDV + QDV + EXMO	18	.369
D13	LPPT15 + QPPT15 + LDV + QDV + EXMO12 to EXMO56	22	.374
D14	Reduced model, deleted nonsignificant variates from Model LEAFN-D8	14	.371
D15	Reduced model, deleted nonsignificant variates from Model LEAFN-D13	15	.371

[a]Base model was Model LEAFN-A10 (Table 11) with 44 variates and R^2 of 0.269.

[b]Symbols of the summation variates are described in Table 3; L, Q, and I represent the four summation variates of a third-order polynomial for the linear, squared, and interaction functions of the 5-day weather indexes, respectively.

actions between DV and PPT had little effect on the R^2, that testing of the PPT15 indexes gave no gain in the R^2 from seven more 5-day precipitation periods, and that replacing the EXMO index by three new excess moisture indexes and the four PPTEM indexes increased the R^2 in Model LEAFN-D10 by only 1%.

To determine if this summation technique gives a good estimation of the effects of the 5-day PPT and DV indexes on LEAFN, the regression coefficients for each 5-day index were estimated from the regression coefficients of the summation variates of these indexes in Model LEAFN-D7 by applying the procedure explained in the previous chapter. From these regression coefficients, the first derivatives were calculated and the rates of change of LEAFN with respect to each 5-day PPT and DV index were obtained by substituting the mean value for each index in the partial derivatives of LEAFN. These rates of change were then compared with the rates of change calculated from the regression coefficients of the linear and squared variates of the eight DV and the eight PPT indexes in Model LEAFN-C21 (without the BARR variable).

Figure 1 depicts the rates of change in LEAFN with respect to each DV index for both the estimated (dashed line) and the directly observed coefficients (solid line). The rates calculated from the estimated coefficients approach those calculated from the directly observed coefficients with a good degree of precision. Likewise, Figure 2 shows the same situation for the PPT indexes. Therefore, these figures show that the summation technique can be used to estimate the effects of these indexes on LEAFN.

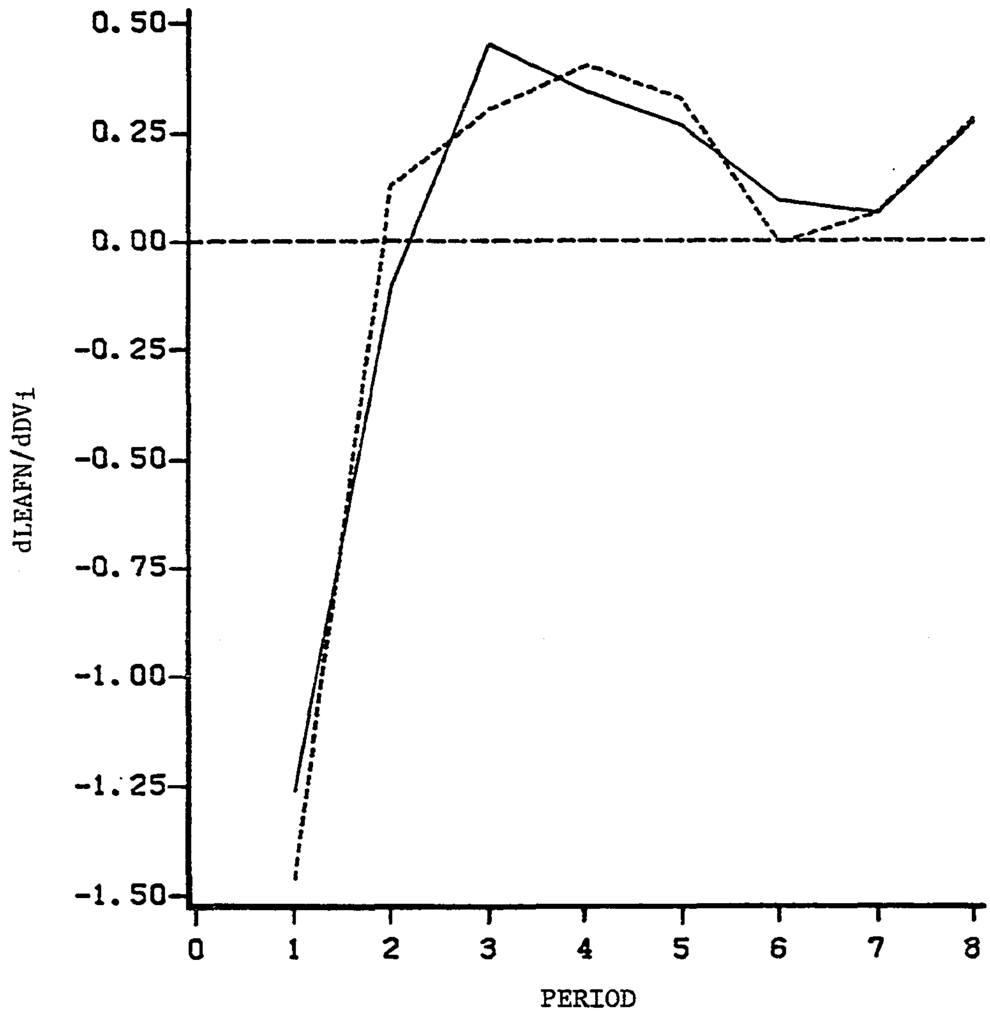

Figure 1. Rates of change of LEAFN with respect to each 5-day DV index as calculated from the directly observed regression coefficients (solid line) and from the estimated coefficients (dashed line)

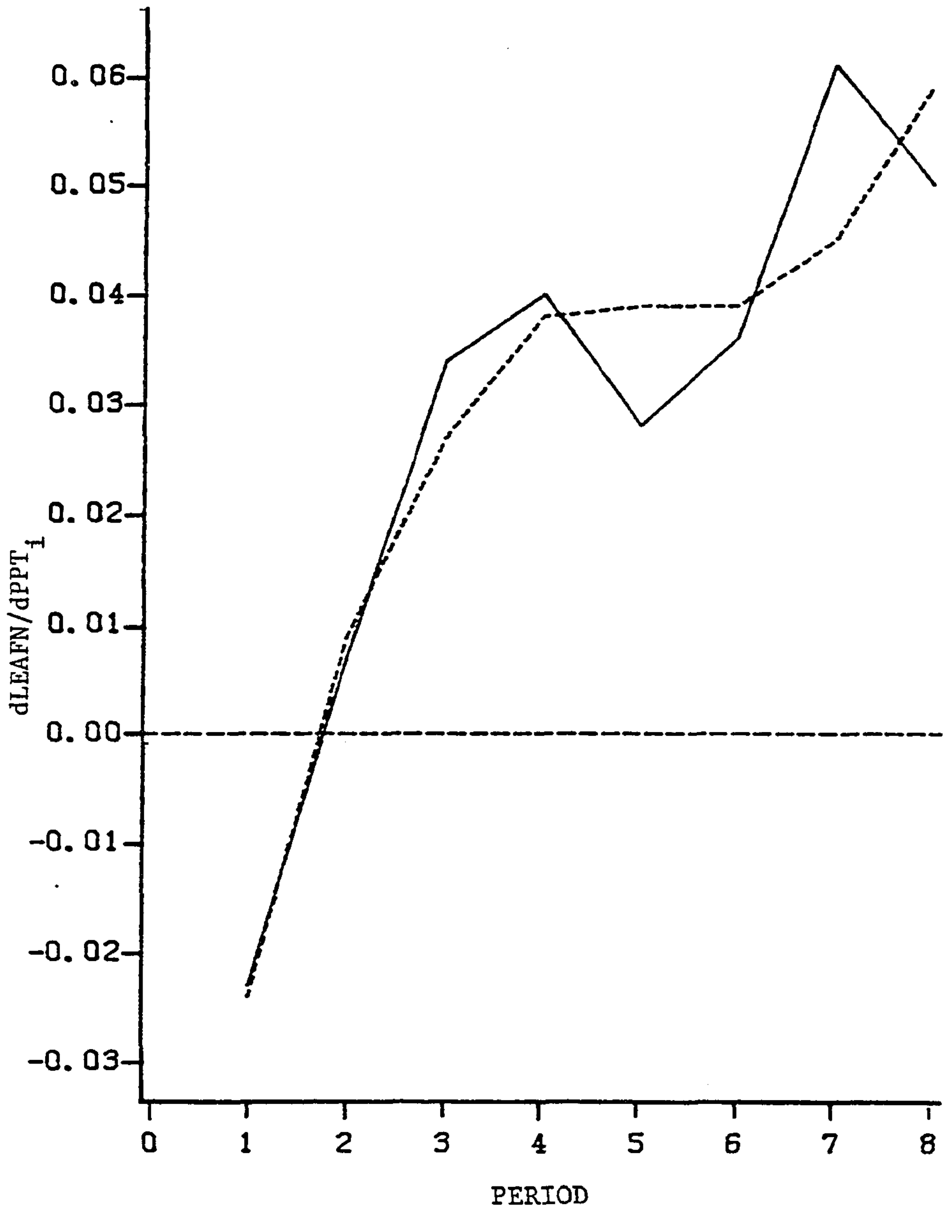

Figure 2. Rates of change of LEAFN with respect to each 5-day PPT index as calculated from the directly observed regression coefficients (solid line) and from the estimated coefficients (dashed line)

These two figures provided the first graphical illustration of how the moisture stress and precipitation indexes across the 40-day period affected the final leaf N concentration. In Figure 1, the rate of change of LEAFN with respect to DV1 revealed the previously indicated, deleterious effect of low stress or high soil moisture on LEAFN during this period (Table 15). The rates of change with respect to the DV3 to DV5 indexes showed again that decreased moisture stress increased LEAFN in these periods. The same response to the DV8 index demonstrated the positive effect that less moisture stress (above its mean) exerted on LEAFN (Table 15).

The effects of the precipitation indexes on changes in LEAFN in Figure 2 showed the same negative effect of high moisture during the first period and the positive effects of moisture, as supplied by rainfall, on LEAFN from the second period on at mean levels of precipitation.

When Fisher's summation technique was described, a third-order polynomial was assumed to represent the relationship between time and the responses of LEAFN to each weather index. Examination of the two figures indicated that the assumed degree of the polynomial was adequate to represent that relationship for the DV indexes, because the curve shows two inflection points in the distribution of the rates of change of LEAFN with respect to the DV indexes. For the PPT indexes, Figure 2 indicated that a second-order polynomial could represent this relationship, although a weak cubic effect was evident. To determine statistically the appropriate order of the polynomial for each type of index, alternative regression models were computed in which nonsignificant summation variates (at the 10% level) were deleted by stepwise, backward elimination.

In this manner, Models LEAFN-D8 and LEAFN-D13 were reduced to get Models LEAFN-D14 and LEAFN-D15 (Table 16), respectively. The regression statistics of the selected weather variates in reduced Model LEAFN-D14 are given in Table 17. All summation variates representing the linear and squared effects of the DV indexes were highly significant except DVQI which was significant at the 5% level. Hence, this confirms the graphical evidence from Figure 1 that the third-order polynomial represents the relationship between time and the distribution of the responses of LEAFN to the 5-day DV indexes in the 40-day period before leaf sampling.

The four summation variates representing the linear effects of the 5-day PPT indexes were significant while only the linear summation variate of the squared function (PPTQL) was significant. This finding appears to agree with the weak cubic relationship shown in Figure 2.

Testing of interactions

The effects on LEAFN of the interactions between the polynomial summation variates of the eight 5-day DV indexes and of the fifteen 5-day PPT15 indexes plus the quadratic function of the EXMO34 index (sum of the EXMO3 and EXMO4 8-day excess moisture indexes) and selected management and soil variables were next ascertained. These weather variates, which had been retained in Model LEAFN-D15, along with the other variates were included in the base interaction model and listed in Table 18. The procedure for this testing was explained in the previous chapter.

To test the interactions, four series of regression models were computed and were designated the Models LEAFN-E to LEAFN-H series.

Table 17. Regression statistics of the summation variates of the weather indexes selected in reduced Model LEAFN-D14[a]

Variate[b]	bi	Variate[b]	bi
DVI	-7.636**	DVQI	12.025*
DVL	6.225**	DVQL	-9.893**
DVQ	-1.246**	DVQQ	1.974**
DVC	0.0727**	DVQC	-0.114**
PPTI	-0.0500**	PPTQI	-
PPTL	0.0451**	PPTQL	-0.00125**
PPTQ	-0.00793*	PPTQQ	-
PPTC	0.000530*	PPTQC	-
EXMO	-0.0147**		
$EXMO^2$	-		

[a]Intercept = 2.25, R^2 = 0.371, and no. of variates = 58.

[b]Variables are as described in Table 3.

Table 19 lists the interaction variates tested in each series. The model selection steps followed in each series are given in Table 20.

In the Model LEAFN-E series, deletion of 27 nonsignificant interaction variates from Model LEAFN-E1 reduced the R^2 from 0.403 to 0.394 in Model LEAFN-E15, but the R^2 of this model was 2.5% higher than that of base Model LEAFN-D15 (Table 16). Selection of 11 of 28 interaction variates in the Model LEAFN-F series increased the R^2 to 0.405 in Model LEAFN-F11 (Table 20).

In the Model LEAFN-G series, only 1 of 17 variates tested was selected with a 0.3% increment in the R^2. Lastly, in the Model LEAFN-H series, another 17 interaction terms were tested; however, only 14 of these were interactions between weather indexes and soil or management

Table 18. Base set of linear and squared variates included in the regression models to select interaction variates, Models LEAFN-E to LEAFN-H series

X_i	Variate	X_i	Variate	X_i	Variate
1	EXMO34	20	PLOW	38	BIO
		21	TILLAFT	39	TILL
2	DVI	22	PLDATE	40	PALEO
3	DVL	23	PLMETH	41	ALLUV
4	DVQ			42	DCAL
5	DVC	24	MANURE		
6	DVQI	25	KROW	43	$SAMDIF^2$
7	DVQL	26	NBDCT	44	$PLDEN^2$
8	DVQQ	27	PBDCT	45	$CB1^2$
9	DVQC			46	$TILLAFT^2$
		28	STN	47	$KROW^2$
10	PPT15I	29	STK1	48	$NBDCT^2$
11	PPT15L	30	NCODE1	49	STN^2
12	PPT15Q	31	HYMAT	50	$NCODE1^2$
13	PPT15QI	32	HYCROSS	51	$HYCROSS^2$
14	PPT15QL			52	$RANGE^2$
		33	TWP	53	CPL^2
15	SAMDIF	34	RANGE	54	BIO^2
16	LEAFN[a]			55	$EXMO34^2$
17	PLDEN	35	THAHOR		
18	CB1	36	CPL		
19	WEEDS	37	DCMAX		

[a]LEAFN was the dependent variable regressed on the listed variates plus selected interaction variates.

Table 19. Interaction variates included in the multiple regressions, Models LEAFN-E to LEAFN-H series[a]

X_i	Model LEAFN-E	X_i	Model LEAFN-F	X_i	Model LEAFN-G	X_i	Model LEAFN-H
56[b]	DVI*PLDEN	55	DVI*NBDCT	55	DVI*NBDCT	55	DVI*NBDCT
57	DVL*	56	DVL*	56	DVL*	56	DVL*
58	DVQ*	57	DVQ*	57	DVQ*	57	DVQ*
59	DVC*	58	DVC*	58	DVC*	58	DVC*
60	DVI*NBDCT	59	DVI*WEEDS	59	DVI*WEEDS	59	DVI*WEEDS
61	DVL*	60	DVL*	60	DVL*	60	DVL*
62	DVQ*	61	DVQ*	61	DVQ*	61	DVQ*
63	DVC*	62	DVC*	62	DVC*	62	DVC*
64	DVI*STN	63	DVI*NCODE1	63	DVI*NCODE1	63	DVI*NCODE1
65	DVL*	64	DVL*	64	DVL*	64	DVL*
66	DVQ*	65	DVQ*	65	DVQ*	65	DVQ*
67	DVC*						
		66	PPT15I*PLDEN	71	DVI*SAMDIF	70	DVI*SAMDIF
68	DVI*NCODE1	67	PPT15L*	72	DVL*	71	DVL*
69	DVL*	68	PPT15Q*	73	DVQ*	72	DVQ*
70	DVQ*	69	PPT15L*STN	74	DVC*	73	DVC*
71	DVC*	70	PPT15I*WEEDS	75	DVI*THAHOR	74	DVI*THAHOR
72	DVI*WEEDS			76	DVL*	75	DVL*
73	DVL*	100	EXMO34*PLDEN	77	DVQ*	76	DVQ*
74	DVQ*			78	DVI*CB1	77	DVI*CB1
75	DVC*	71[b]	DVI*SAMDIF				
		72	DVL*	66	PPT15I*PLDEN	66	PPT15I*PLDEN
76	PPT15I*PLDEN	73	DVQ*	67	PPT15L*	67	PPT15Q*
77	PPT15L*	74	DVC*	68	PPT15Q*	68	PPT15L*STN
78	PPT15Q*	75	DVI*THAHOR	69	PPT15L*STN	69	PPT15I*WEEDS
		76	DVL*	70	PPT15I*WEEDS	78	PPT15L*SAMDIF

[a]Variate 93 was a dummy variable; in Models LEAFN-F to LEAFN-H, $CB1^2$ was deleted.

[b]This variate and the variates below it were the new interaction variates added for testing.

Table 19. (Continued)

X_i	Model LEAFN-E	X_i	Model LEAFN-F	X_i	Model LEAFN-G	X_i	Model LEAFN-H
79	PPT15I*NBDCT	77	DVQ*THAHOR	79	PPT15L*SAMDIF	79	PPT15I*CB1
80	PPT15L*	78	DVC*	80	PPT15I*CB1	80	PPT15L*
81	PPT15Q*	79	DVI*CB1	81	PPT15L*	99	EXMO34*DCMAX
82	PPT15I*STN	80	DVL*	100	EXMO34*PLDEN	100	*PLDEN
83	PPT15L*	81	DVQ*				
84	PPT15Q*	82	DVC*	82[b]	DVI*HYCROSS	81[b]	DVI*DCMAX
		83	DVI*BIO	83	DVL*	82	DVL*
85	PPT15I*NCODE1	84	DVL*	84	DVQ*	83	DVQ*
86	PPT15L*	85	DVQ*	85	DVC*	84	DVC*
87	PPT15Q*	86	DVC*	86	DVI*TWP	85	DVI*PLDATE
88	PPT15I*WEEDS			87	DVL*	86	DVL*
89	PPT15L*	87	PPT15I*SAMDIF	88	DVQ*	87	DVQ*
90	PPT15Q*	88	PPT15L*	89	DVC*	88	DVC*
		89	PPT15Q*				
91	EXMO34*PLDEN	90	PPT15I*THAHOR	90	PPT15I*HYCROSS	89	PPT15I*DCMAX
92	*NBDCT	91	PPT15L*	91	PPT15L*	90	PPT15L*
94	*STN	92	PPT15Q*	92	PPT15Q*	91	PPT15Q*
95	*NCODE1	94	PPT15I*CB1	94	PPT15I*TWP	94	PPT15I*PLDATE
96	*WEEDS	95	PPT15L*	95	PPT15L*	95	PPT15L*
97	*RANGE	96	PPT15Q*	96	PPT15Q*	96	PPT15Q*
98	*CPL	97	PPT15I*BIO	97	EXMO34*TWP	92	STN*NCODE1
99	*BIO	98	PPT15L*	98	*DCMAX	97	NBDCT*STN
100	*CB1	99	PPT15Q*	99	*PLOW	98	*NCODE1

Table 20. Model selection steps, Models LEAFN-E to LEAFN-H series

Model no.	No. of X_i	Identification	R^2
LEAFN-E1	98	Complete model, base set of 55 variates (Table 19) plus 44 interaction variates	.403
E15	71	Reduced model, base set plus 17 selected interaction variates	.394
F1	98	Complete model, variates in Model LEAFN-E15 except $CB1^2$ plus 28 interaction variates	.411
F11	81	Reduced model, variates in Model LEAFN-E15 except $CB1^2$ plus 11 selected interaction variates	.405
G1	98	Complete model, variates in Model LEAFN-F11 plus 17 interaction variates	.412
G10	81	Reduced model, variates in Model LEAFN-F11 except PPT15L*PLDEN plus 1 selected interaction variate	.408
H1	98	Complete model, variates in Model LEAFN-G10 plus 17 interaction variates	.427
H7	89	Reduced model, variates in Model LEAFN-G10 plus 8 selected interaction variates	.426

variables and the other 3 were the STN*NCODE1, STN*NBDCT, and NBDCT*NCODE1 interactions. Only 5 of the 14 first-mentioned interaction variates but all three of the other interactions were retained.

Reduced Model LEAFN-H7 included 36 significant interaction variates, of which 22 were interactions between summation variates of the DV indexes and the NBDCT, WEEDS, NCODE1, SAMDIF, THAHOR, CB1, and DCMAX variables. On the other hand, only 9 interaction variates between summation variates of the PPT15 indexes and PLDEN, STN, WEEDS, SAMDIF, CB1, DCMAX, and PLDATE were retained. The EXMO34 index interacted significantly only with the DCMAX and PLDEN variables. The R^2 of the LEAFN-H7 model was 0.426, an increment of 5.7% with respect to the R^2 of the LEAFN-D15 base model.

As explained in the preceding chapter, several interactions within the group of soil and management variables were next tested. The procedure used was similar to the one used in the previous stage. Table 21 gives the interactions tested in each of the two additional Model LEAFN-I and LEAFN-J series and Table 22 summarizes the model selection steps.

In the Model LEAFN-I series, only 2 of the 10 interactions tested were retained in Model LEAFN-I5, with almost no change in the R^2. In the Model LEAFN-J series, 7 new interactions were tested but none was significant. Because this was the last series, a stepwise, backward elimination was applied to select, besides the added interactions, only the significant variates (at the 5% level) of the weather, soil, and management variables. In this way, final Model LEAFN-J24 was obtained which had 76 variates and an R^2-value of 0.419.

Model LEAFN-J24 was regarded as the final prediction model of LEAFN (leaf N concentration) on selected variates of weather, soil, and management variables. This model explained only about 42% of the variability observed in the leaf N concentration at silking time under the conditions prevailing in Iowa over a span of 10 years. However, this model accounted for about 15% more variability than the base model including only the linear and squared functions of selected soil and

Table 21. Interaction variates tested in the multiple regression Models LEAFN-I and LEAFN-J series

X_i[a]	Model LEAFN-I	X_i[a]	Model LEAFN-J
88	NBDCT*CPL	91	NBDCT*BIO
89	STN*MANURE	92	*PLDATE
90	*WEEDS	94	*THAHOR
91	*BIO	95	*TILL
92	*HYCROSS		
94	*PLDATE	96	NCODE1*KROW
		97	*STK1
95	NBDCT*WEEDS	98	*PBDCT
96	*PLDEN		
97	TILLAFT*WEEDS		
98	STK1*KROW		

[a]X_{93} was the dummy variable in the HELARCTOS II program.

management variables (Model LEAFN-A10, Table 10). Most of this improvement was due to the variates of the weather indexes included.

In regard to the weather indexes, a significant improvement was obtained from recognizing and quantifying their variability through the period of the growing season prior to leaf sampling as evidenced by the differences observed between models including the overall excess moisture, precipitation, and moisture stress indexes and models including the same indexes estimated for continuous small intervals. Besides the quantitative improvements, a substantial understanding of the relationships between the leaf N concentration and the weather factors and their variability was achieved.

Table 22. Model selection steps, Models LEAFN-I and LEAFN-J series

Model no.	No. of X_i	Identification	R^2
LEAFN-I1	98	Complete model, variates in Model LEAFN-H7 plus 10 interaction variates[a]	.428
I5	90	Reduced model, variates in Model LEAFN-H7 plus 2 selected interaction variates	.427
J1	98	Complete model, variates in Model LEAFN-I5 plus 7 interaction variates (NBDCT*NCODE1 was reset in the model)	.433
J15	84	Reduced model, variates in Model LEAFN-I5 plus previously selected NBDCT*NCODE1 interaction	.427
J24	76	Final interaction model, deleted 8 non-significant variates from Model LEAFN-J15	.419

[a]The previously selected NBDCT*NCODE1 variate was omitted and the NBDCT*CPL was included instead. It was reset into Model LEAFN-J series.

Interpretation of final prediction Model LEAFN-J24

The regression statistics of the final interaction Model LEAFN-J24 are shown in Table 23. The effects on LEAFN of the weather, soil, and management variables represented by the variates included in this model will be next discussed.

Weather indexes The EXMO34 index, which is the accumulated excess moisture index for the third and fourth 8-day periods from 3 days after planting, decreased LEAFN at a decreasing rate over most of the relevant range (Table 23). Its effect was modified by positive interactions with PLDEN and DCMAX, as shown by the partial derivative of dLEAFN/dEXMO34 =

Table 23. Regression statistics of the final interaction Model LEAFN-J24[a]

X_i	Variate[b]	b_i	X_i	Variate	b_i
1	EXM034 (0.42)	-0.201**	46	$KROW^2$	0.000104**
2	DVI (2.18)	-2.721**	47	$NBDCT^2$	-0.0000108**
3	DVL (11.40)	2.779**	48	STN^2	-0.0000986**
4	DVQ (70.47)	-0.562**	49	$NCODE1^2$	0.000345**
5	DVC (473.26)	0.0312**	50	$HYCROSS^2$	0.0275**
6	DVQI	-3.698**	52	CPL^2	-0.000160*
7	DVQL	0.550**	54	$EXM034^2$	0.00747*
10	PPT15I (11.20)	-0.00304	55	DVI*NBDCT	0.0293**
11	PPT15L (-2.36)	0.00678**	56	DVL*	-0.0237**
12	PPT15Q (210.80)	0.00196**	57	DVQ*	0.00499**
13	PPT15QI	-0.00358**	58	DVC*	-0.000309**
			59	DVI*WEEDS	-0.0199**
15	SAMDIF (0.8)	0.0472	60	DVL*	0.0164**
17	PLDEN (380)	-0.00145**	61	DVQ*	-0.00376**
18	CB1 (3)	-0.0120**	62	DVC*	0.000257**
19	WEEDS (60)	0.000135			
20	PLOW (0.7)	-0.0437**	63	DVI*NCODE1	-0.0497*
21	TILLAFT (4)	0.0327*	64	DVL*	0.0232*
22	PLDATE (23)	0.00873**	65	DVQ*	-0.00226*
23	PLMETH (0.4)	0.0371**	70	DVI*SAMDIF	-0.108*
			71	DVL*	0.0171*
24	MANURE (5)	0.00226**	74	DVI*THAHOR	0.0396**
25	KROW (11)	-0.00582**	75	DVL*	-0.0170**
26	NBDCT (68)	0.00461**	76	DVQ*	0.00155*
28	STN (63)	0.0167**			
29	STK1 (226)	0.000183**	66	PPT15I*PLDEN	0.0000599*
30	NCODE1 (23)	-0.0291**	67	PPT15Q*	-0.00000290*
31	HYMAT (3)	-0.0172*	68	PPT15L*STN	-0.0000751**
32	HYCROSS (2)	-0.140**	69	PPT15I*WEEDS	-0.0000464*
33	TWP (20)	0.00410**	78	PPT15L*SAMDIF	-0.000467*
35	THAHOR (34)	-0.00243	79	PPT15I*CB1	0.00107*
36	CPL (26)	0.00608	80	PPT15L*	0.000197*
37	DCMAX (54)	0.00174**	84	PPT15Q*DCMAX	-0.00000569*
38	BIO (5)	0.0160*	85	PPT15I*PLDATE	-0.000486*
39	TILL (0.25)	-0.0521**			
40	PALEO (0.03)	-0.162**	86	STN*NCODE1	0.000125**
41	ALLUV (0.1)	-0.0608**	87	NBDCT*STN	-0.0000548**
42	DCAL (30)	-0.000593**	88	*NCODE1	0.0000307**
			90	*PLDEN	0.00000559**
43	$SAMDIF^2$	-0.00642**	99	EXM034*DCMAX	0.00102**
45	$TILLAFT^2$	-0.00402**	100	*PLDEN	0.000192*

[a]Intercept = 1.977** and R^2 = 0.419.

[b]Variable means are listed in the parentheses.

-0.201 + 0.0149 EXMO34 + 0.000192 PLDEN + 0.00102 DCMAX. At PLDEN = 500 (50,000 plants/ha) and DCMAX = 60 cm (24 in.), the simplified partial derivative = -0.044 + 0.0149 EXMO34 which showed that minimum LEAFN occurred at EXMO34 = 2.95, considerably higher than its mean of 0.42. The rate of change of LEAFN with respect to EXMO34 became less negative as both plant density and depth to maximum clay horizon increased, i.e., the detrimental effect of EXMO34 on LEAFN decreased as the level of either interacting variable increased.

As explained in the Data Sources and Procedures chapter, the rates of change of LEAFN with respect to each 5-day DV and PPT15 index can be obtained by, first, estimating the regression coefficients for the linear, squared, and interaction functions of each index from the coefficients of the respective summation variates and, second, by taking the partial derivatives of LEAFN with respect to each 5-day index. Table 24 presents the first partial derivatives that were calculated for each of the eight 5-day DV indexes.

The derivatives in Table 24 show that the rates of change of LEAFN with respect to the 5-day DV indexes varied across the 40-day period (eight 5-day periods) before the leaf sampling date. The linear components of the 5-day DV indexes (shown in the C or constant column in Table 24) varied in a cubic manner from DV1 to DV8. They increased from a negative value for DV1 to a maximum and positive for DV3 and DV4. They then decreased to a negative one for DV7 and then to a more negative one, but at a decreasing rate for DV8 because of the third-order or cubic function of the DV linear components (DVI to DVC) shown in Table 23.

Table 24. First partial derivatives of LEAFN on each 5-day DV index, calculated from the estimated regression coefficients in Model LEAFN-J24

$dLEAFN/dDV_i$ for following DV_i[a]	Coefficients of the quadratic function of DV_i and its interactions with the following variables in the partial derivatives						
	C	DV_i	NBDCT	WEEDS	NCODE1	SAMDIF	THAHOR
DV1	-0.473	-6.296	0.0103	-0.00702	-0.0288	-0.0910	0.0242
DV2	0.837	-5.195	-0.000548	-0.000141	-0.0124	-0.0738	0.0118
DV3	1.399	-4.095	-0.00514	0.00230	-0.000549	-0.0567	0.00260
DV4	1.398	-2.995	-0.00530	0.00184	0.00679	-0.0396	-0.00353
DV5	1.023	-1.894	-0.00289	0.000021	0.00961	-0.0224	-0.00656
DV6	0.460	-0.794	0.000240	-0.00161	0.00790	-0.00532	-0.00649
DV7	-0.102	0.306	0.00223	-0.00152	0.00167	0.0118	-0.00332
DV8	-0.477	1.407	0.00123	0.00184	-0.00908	0.0289	0.00295

[a]First partial derivatives of LEAFN with respect to each 5-day DV index, where i = 1, 2, ..., 8.

The total rates of change of LEAFN were also modified by the respective quadratic components of these indexes (shown in the DV_i column of Table 24). These increased linearly from a negative value for DV1 to a positive value for DV8, as determined by the significant DVQI and DVQL variates in Table 23.

The linear rates of change of LEAFN (in the C column of Table 24) were also modified by the levels of the interacting variables of NBDCT, WEEDS, NCODE1, SAMDIF, and THAHOR. At fixed levels of the interacting variables, the constant in the partial derivative for each DV_i was increased or decreased depending on the sign of the interaction with the DV_i variate. Because each DV_i has only a quadratic effect on LEAFN, the interaction effect modifies the constant in the derivative to increase or decrease the initial slope at the intercept ($DV_i = 0$) and the DV_i values associated with the maximum or minimum LEAFN. Over the eight 5-day periods from DV1 to DV8, the values of the coefficients for the interactions with NBDCT and WEEDS varied in a cubic manner, those with NCODE1 and THAHOR varied in a quadratic manner, and that with SAMDIF varied in a linear manner, as shown by their interactions with the various summation variates (DVI, DVL, DVQ, and DVC in Table 23).

The mean rates of change of LEAFN to each 5-day DV index were calculated by substituting into the partial derivatives (Table 24) the mean values of the respective DV index and of all the interacting variables. The rates so obtained are graphically shown in Figure 3, which shows that the rates of change of LEAFN to the DV indexes changed from a negative rate of change of LEAFN to DV1 to a maximum, positive rate

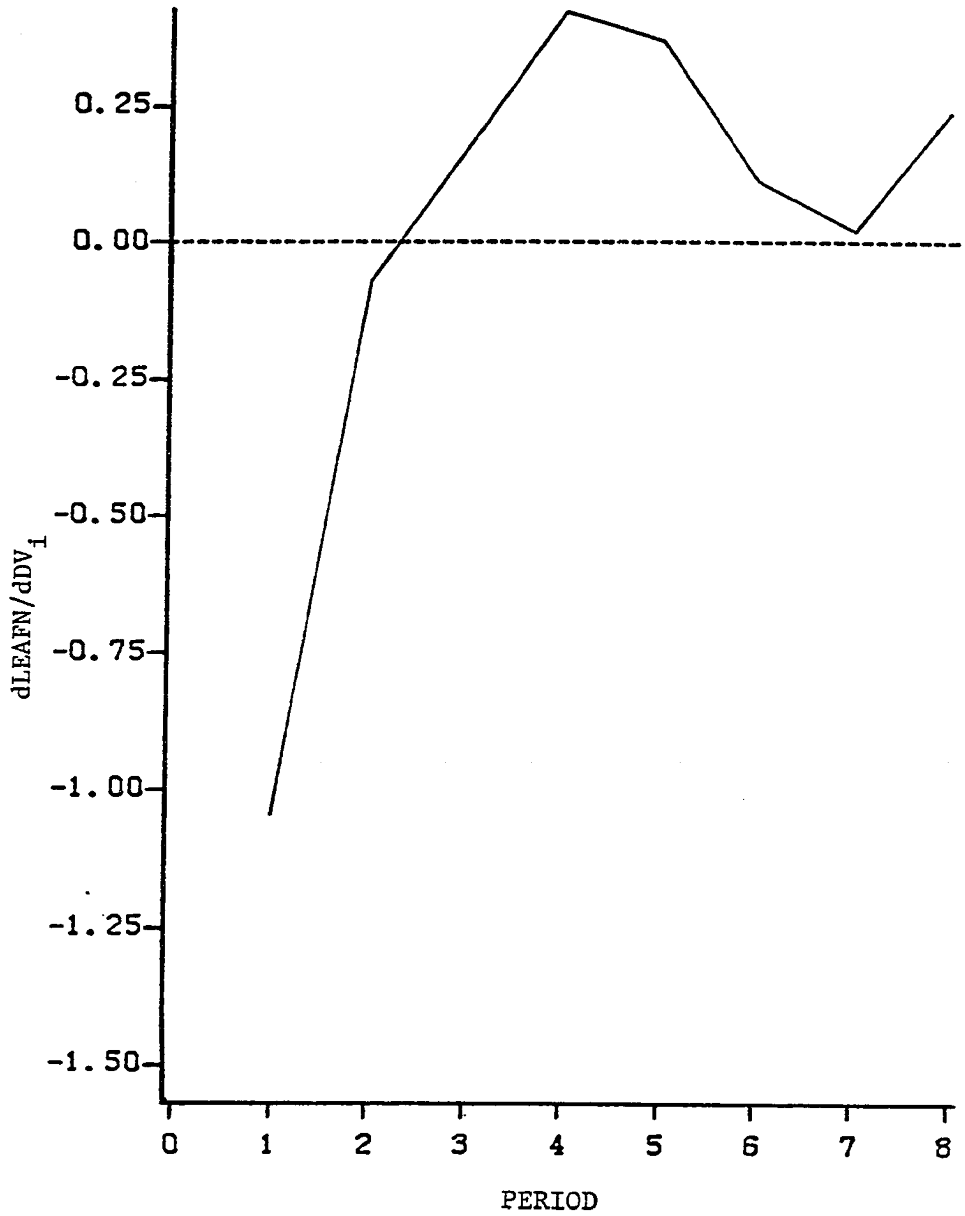

Figure 3. Rates of change of LEAFN with respect to each 5-day DV index at average values of all variables included in the first partial derivatives (Table 24)

of change to DV4. Thereafter, the rates of change decreased to a minimum to DV7 and, at this point, a second inflection of the curve led to a higher rate of change to DV8. These cubic changes in LEAFN with respect to time (DV1 to DV8 periods) were similar to those illustrated in Figure 1; therefore, their agronomic interpretation is also similar to that given previously.

Discussion of the effects of all the interactions between the DV indexes and the 5 variables shown in Tables 23 and 24 could be lengthy. Hence, only the interactions between the DV indexes and the NBDCT and SAMDIF variables will be discussed.

In order to illustrate the interactions between the 5-day DV indexes and the NBDCT variable on LEAFN, the first partial derivatives were simplified for values of NBDCT of 25 and 150 kg of N/ha. The other interacting variables were set at the following values: WEEDS = 5, NCODE1 = 20, SAMDIF = 1, and THAHOR = 25. The simplified derivatives for both levels of NBDCT as well as the values of each DV index associated with maximum or minimum LEAFN are presented in Table 25.

First, the regression coefficients associated with these interactions (Table 24) indicated that higher levels of NBDCT increased the curvilinear responses of LEAFN to the DV indexes in periods 1, 7, and 8. However, higher levels of NBDCT decreased the responses of LEAFN to the DV indexes in periods 3, 4, and 5. In periods 2 and 6, effects of NBDCT on responses to DV were small.

As shown in Table 25, the effect of the moisture stress index on LEAFN, as affected by NBDCT levels, varied across the 40-day period before

Table 25. Simplified first partial derivatives of LEAFN on each 5-day DV index at two levels of NBDCT, final Model LEAFN-J24

NBDCT (kg N/ha)	Simplified $dLEAFN/dDV_i$ =	Quadratic effect[b]	DV_i[a] Mean	Range
25	-0.313 - 6.30 DV1	MAX at -0.05	0.15	0.01-0.2
	0.796 - 5.20 DV2	MAX at 0.15	0.18	0.04-0.3
	1.279 - 4.10 DV3	MAX at 0.31	0.25	0.08-0.4
	1.283 - 3.00 DV4	MAX at 0.43	0.24	0.07-0.4
	0.956 - 1.89 DV5	MAX at 0.50	0.23	0.05-0.4
	0.448 - 0.79 DV6	MAX at 0.56	0.29	0.04-0.5
	-0.092 + 0.31 DV7	MIN at 0.30	0.40	0.05-0.6
	-0.516 + 1.41 DV8	MIN at 0.37	0.43	0.06-0.7
150	0.977 - 6.30 DV1	MAX at 0.15	-	-
	0.728 - 5.20 DV2	max at 0.14	-	-
	0.636 - 4.10 DV3	MAX at 0.15	-	-
	0.620 - 3.00 DV4	MAX at 0.21	-	-
	0.595 - 1.89 DV5	MAX at 0.31	-	-
	0.478 - 0.79 DV6	MAX at 0.60	-	-
	0.187 + 0.31 DV7	MIN at -0.61	-	-
	-0.362 + 1.41 DV8	MIN at 0.25	-	-

[a]The DV_i (DV1 to DV8) means and ranges are listed in order; those associated with NBDCT = 150 are the same as listed for NBDCT = 25.

[b]Values of the DV_i indexes associated with maximum (MAX) or minimum (MIN) LEAFN.

leaf sampling date. The initial slopes at the Y intercept, the magnitudes of the positive or negative LEAFN responses (not shown but can be calculated from the simplified derivatives), and the DV levels associated with maximum or minimum LEAFN were affected by the interactions with NBDCT. The differences between the DV levels in each of the 5-day periods associated with maximum or minimum LEAFN illustrate the interaction effects of NBDCT. In most cases, the direction of the rate of change in LEAFN changed from positive to negative or vice versa within the relevant ranges.

In the first 5-day period, increasing DV1 decreased LEAFN throughout the relevant range at the low rate of NBDCT, but it increased LEAFN up to DV1 = 0.15 and then decreased it at the high rate of NBDCT (Table 25). The effect of increasing DV (higher soil moisture) early in the 40-day period on LEAFN at the low N availability agrees with the results reported by Lal and Taylor (1970). In both periods 2 and 6 (transition periods), NBDCT had no effect on the rate of change of LEAFN with respect to DV.

Similar interaction effects on LEAFN between DV and NBDCT occurred in periods 3, 4, and 5. At the low NBDCT level, DV increased LEAFN over most to all of its relevant range but, at the high NBDCT level, DV increased LEAFN up to about the mean DV levels and then decreased LEAFN. In the last two periods (7 and 8), the effects of DV on LEAFN were reversed, with low DV levels decreasing LEAFN and moderate to high DV levels then increasing LEAFN. At the high NBDCT level, the DV effects were positive on LEAFN over more of its relevant range than at the low NBDCT level.

In periods 3 to 5, higher DV levels (greater soil moisture levels) were required to obtain the maximum LEAFN at low than at high NBDCT levels. This may reflect the need to maintain moist conditions in the plow layer in order to increase the mineralization of soil organic N and nitrification of sidedressed NH_3 fertilizer. In the last two periods, the reason for the decrease in LEAFN at the very low DV levels to a minimum is not known. The positive effect of DV on LEAFN over more of the relevant range with high than with low NBDCT parallels the positive NBDCT*DV interaction on corn yield reported by Sridodo (1980) and others. Because higher soil moisture was required to increase LEAFN if available N was low than if it was high, this indicated that applied N offset the effects of moisture stress to some extent in the 2 to 12 days prior to leaf sampling date.

To illustrate the interactions between the 5-day DV indexes and the SAMDIF (difference between 75% silking date and sampling date) variable, the first derivatives were simplified for the values of SAMDIF of 2 and -2, which means that leaf samples were taken two days before and two days after the estimated 75% silking date, respectively. Other interacting variables were set at NBDCT = 125, WEEDS = 5, NCODE1 = 20, and THAHOR = 25. The simplified derivatives as well as the values of the DV indexes associated with maximum or minimum LEAFN at each level of SAMDIF are given in Table 26.

The coefficients of the DV_i*SAMDIF interactions listed in Table 24 showed that, as SAMDIF changes from positive (sampled before silking) to negative (sampled after silking), it decreases the C (constant) and thus the curvilinear responses of LEAFN to the DV indexes and then increases the C (constant) and the responses during each of the first six periods. In the last two periods (7 and 8), the effects on LEAFN of the DV indexes from sampling before and after silking were reversed because of the sign reversal of the DV_i*SAMDIF interactions. Table 24 also showed that the coefficients of the DV_i*SAMDIF interactions increased linearly (became

Table 26. Simplified first partial derivatives of LEAFN on each 5-day DV index at two leaf sampling dates in relation to the silking date, final Model LEAFN-J24

SAMDIF (days)[a]	Simplified $dLEAFN/dDV_i$ =	Quadratic effect[b]
2 (2 days before)	0.628 - 6.30 DV1	MAX at 0.10
	0.668 - 5.20 DV2	MAX at 0.13
	0.708 - 4.10 DV3	MAX at 0.17
	0.713 - 3.00 DV4	MAX at 0.24
	0.645 - 1.89 DV5	MAX at 0.34
	0.467 - 0.79 DV6	MAX at 0.59
	0.143 + 0.31 DV7	MIN at -0.47
	-0.364 + 1.41 DV8	MIN at 0.26
-2 (2 days after)	0.992 - 6.30 DV1	MAX at 0.16
	0.963 - 5.20 DV2	MAX at 0.18
	0.935 - 4.10 DV3	MAX at 0.23
	0.871 - 3.00 DV4	MAX at 0.29
	0.734 - 1.89 DV5	MAX at 0.39
	0.488 - 0.79 DV6	MAX at 0.61
	0.096 + 0.31 DV7	MIN at -0.31
	-0.480 + 1.41 DV8	MIN at 0.34

[a]SAMDIF (difference between silking and leaf sampling dates) = SLKDTE - SAMDTE; mean SAMDIF = 0.8 and range of observations = 8 to -6.

[b]Values of the DV_i indexes associated with maximum (MAX) or minimum (MIN) LEAFN; means and ranges of DV_i were given in Table 25.

less negative and then positive) from DV1 to DV8 because only DVI and DVL interacted with SAMDIF (Table 23).

As shown in Table 26, the effect of soil moisture stress on LEAFN varied across the 40-day period before leaf sampling (as was also shown in Table 25). The effects of the SAMDIF variable on the DV effects, however, were small. From leaf sampling 2 days before silking to 2 days after silking, the levels of the DV indexes associated with maximum

LEAFN increased slightly in the first six periods. In period 7, SAMDIF had little effect on the positive effect of DV7 throughout its range on LEAFN. In period 8, minimum LEAFN occurred at a lower DV8 level if the leaf sampling was before than after silking. It appears that a higher soil moisture level is needed in the earlier periods to maintain the maximum LEAFN as leaf sampling is delayed. The behavior of the DV_i*SAMDIF interactions in the last two periods is different. It shows that LEAFN was increased more with better soil moisture conditions if leaf sampled early than late. These effects may be related to rapid translocation of N from the leaf to the developing ear shoot during the silking stage.

The effects of the other variables interacting with the DV indexes on LEAFN, although having different magnitudes, as evidenced by their different regression coefficients in Table 24, had very similar trends to those of the interactions between the DV indexes and the NBDCT variable. The effects of these interactions were partly related to the plant availability of N, as affected by the weed infestation (decreasing N availability), number of years after a legume or meadow crop (decreasing N availability), or the thickness of the A horizon (increasing N availability). They also were related to plant available water, such as less with increased WEEDS, frequently less if crop is 1st-year corn after meadow, and better moisture intake and water-holding capacity as thickness of the high organic matter A horizon increases.

The rates of change of LEAFN with respect to each of the fifteen 5-day PPT15 indexes were calculated by a procedure similar to that applied to get the rates of change of LEAFN with respect to each DV index.

Table 27 shows the partial derivatives of LEAFN with respect to each of the PPT15 indexes. The linear components of the 5-day PPT15 indexes (shown in the C or constant column in Table 27) varied in a quadratic manner over the 15 periods, decreasing to a minimum in period 6 and then increasing at an increasing rate, because of the significant second-order polynomial of the linear components (PPT15I, PPT15L, and PPT15Q) shown in Table 23. These rates of change were modified by a constant amount due to the significant PPT15QI quadratic variate for the intercept (Table 23).

Finally, these partial derivatives in Table 27 also showed that the linear rates of change of LEAFN with respect to each PPT15 index were increased or decreased by the levels of the PLDEN, STN, SAMDIF, CB1, DCMAX, WEEDS, and PLDATE variables, depending on the signs of the interactions. Over the fifteen 5-day periods, the values of the coefficients for the PPT15 interactions with PLDEN and DCMAX varied in a quadratic manner, those with STN, SAMDIF, and CB1 varied in a linear manner, and those with WEEDS and PLDATE were constant, as shown by their interactions with the various PPT15I, PPT15L, and PPT15Q variates in Table 23.

The mean values of each PPT15 index were substituted into the partial derivatives (Table 27), maintaining all other variables at their average values, and the rates of change of LEAFN with respect to each PPT15 index were obtained. These rates were plotted in Figure 4. The rates of change of LEAFN to the PPT15 indexes varied quadratically, decreasing at a decreasing rate to a minimum in periods 5 to 7 and then increasing at an increasing rate to much larger rates in the several

Table 27. First partial derivatives of LEAFN on each 5-day PPT15 index, calculated from the estimated regression coefficients in Model LEAFN-J24

dLEAFN/dPPT15-i for following PPT15-i[b]	Coefficients of the linear function of PPT15-i and of the interactions between PPT15 indexes and the following variables in the partial derivatives[a]					
	C	PLDEN	STN	SAMDIF	CB1	DCMAX
PPT15-1	0.0457	-0.0000821	0.000525	0.00327	-0.000307	-0.000279
PPT15-2	0.0270	-0.0000444	0.000450	0.00280	-0.000110	-0.000205
PPT15-3	0.0122	-0.0000125	0.000375	0.00233	0.000087	-0.000142
PPT15-4	0.00126	0.0000136	0.000300	0.00187	0.000284	-0.000091
PPT15-5	-0.00570	0.0000339	0.000225	0.00140	0.000481	-0.000051
PPT15-6	-0.00874	0.0000484	0.000150	0.000934	0.000678	-0.000023
PPT15-7	-0.00785	0.0000571	0.000075	0.000467	0.000875	-0.000006
PPT15-8	-0.00303	0.0000600	0.0	0.0	0.00107	0.0
PPT15-9	0.00570	0.0000571	-0.000075	-0.000467	0.00127	-0.000006
PPT15-10	0.0184	0.0000484	-0.000150	-0.000934	0.00147	-0.000023
PPT15-11	0.0350	0.0000339	-0.000225	-0.00140	0.00166	-0.000051
PPT15-12	0.0555	0.0000136	-0.000300	-0.00187	0.00186	-0.000091
PPT15-13	0.0799	-0.0000125	-0.000375	-0.00233	0.00206	-0.000142
PPT15-14	0.108	-0.0000444	-0.000450	-0.00280	0.00225	-0.000205
PPT15-15	0.141	-0.0000821	-0.000525	-0.00327	0.00245	-0.000279

[a]Other coefficients in the partial derivatives for all 15 periods are: -0.00716 PPT15-i, -0.0000464 WEEDS, and -0.000486 PLDATE.

[b]First partial derivatives of LEAFN with respect to each 5-day PPT15 index, where i = 1, 2, ..., 15.

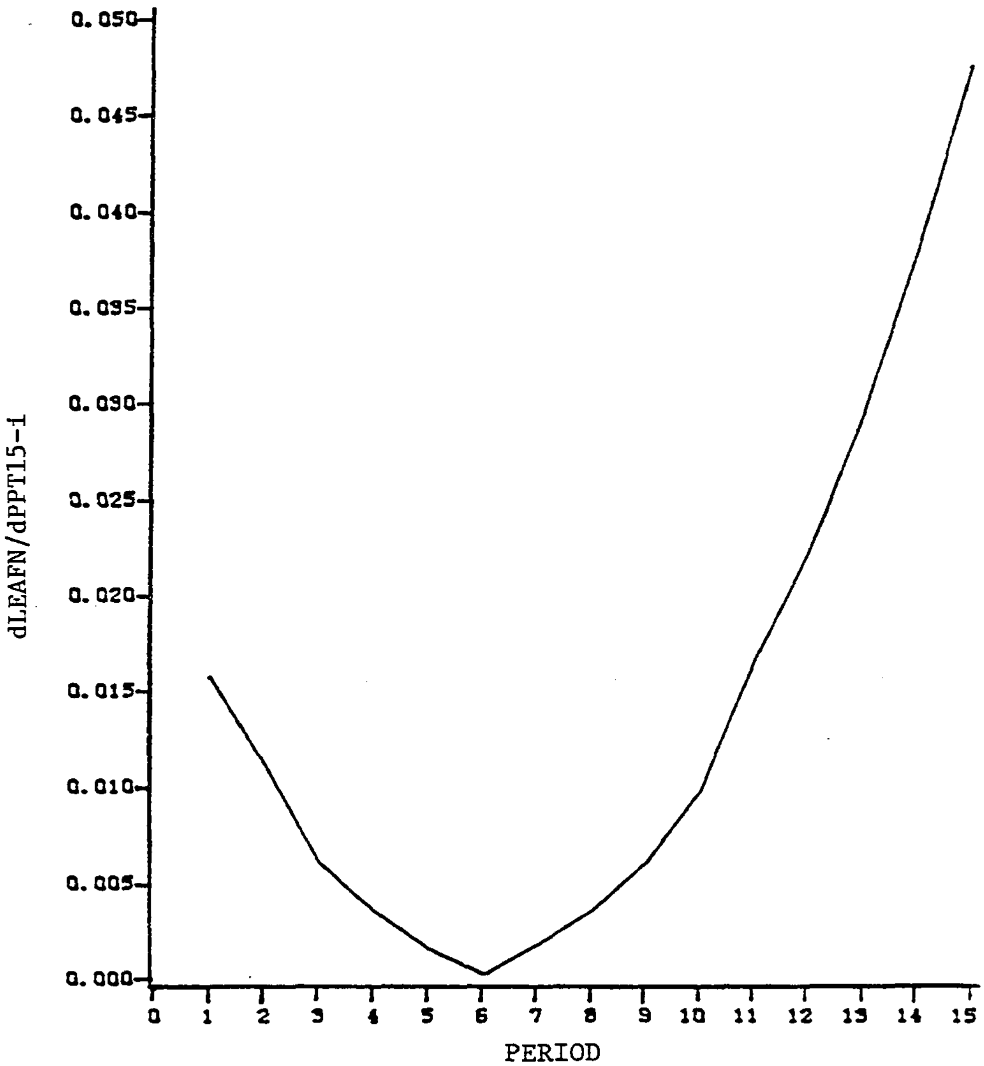

Figure 4. Rates of change of LEAFN with respect to each 5-day PPT15 index at average values of all variables in the first partial derivatives (Table 27)

periods prior to the leaf sampling date. Only the interactions between the PPT15 indexes and the PLDEN and STN variables will be discussed in this section.

To illustrate the interactions between the PPT15 indexes and the PLDEN variable on LEAFN, the first partial derivatives (Table 27) were simplified for values of PLDEN of 300 and 600 plants/0.01 ha (30,000 and 60,000 plants/ha) and the other interacting variables were set at STN = 65, WEEDS = 5, SAMDIF = 1, CB1 = 3, DCMAX = 54, and PLDATE = 23. The simplified derivatives for both levels of PLDEN as well as the values of the PPT15 indexes associated with maximum LEAFN are listed in Table 28.

First, the coefficients associated with the interactions between the PPT15 indexes and PLDEN (Table 27) showed that higher levels of PLDEN decreased the curvilinear responses of LEAFN to the PPT15 indexes in the first 3 periods and in the last 3 periods, while higher levels of PLDEN increased these responses in periods 4 to 12.

As shown in Table 28, the levels of the PPT15 indexes associated with maximum LEAFN were less at the high level than at the low level of PLDEN in the first three and last three 5-day periods. In the middle 9 periods, PPT15 levels associated with maximum LEAFN were higher at the high PLDEN level than at the low PLDEN level. At the higher PLDEN level, the PPT15 levels at maximum LEAFN were considerably higher than the mean PPT15 levels for the 5-day periods.

The effects of PPT15 early in the season were not the expected responses to increased soil moisture because excess moisture early generally decreases LEAFN levels. Also, PLDEN differences so early in the season

Table 28. Simplified first partial derivatives of LEAFN on each 5-day PPT15 index at two levels of PLDEN and at two levels of STN, final Model LEAFN-J24

PPT15 index	Constant in partial derivative[b]	PPT15-i at MAX LEAFN	Constant in partial derivative[b]	PPT15-i at MAX LEAFN	PPT15-i (in.)[a] Mean	Range
	PLDEN = 30,000/ha		PLDEN = 60,000/ha			
PPT15-1	0.031	4.3	0.006	0.9	0.77	0-8.2
2	0.023	3.2	0.010	1.4	0.90	0-6.8
3	0.016	2.3	0.013	1.8	0.81	0-7.5
4	0.011	1.6	0.015	2.2	0.77	0-10.7
5	0.008	1.1	0.018	2.5	0.81	0-8.1
6	0.006	0.8	0.020	2.8	0.62	0-6.2
7	0.005	0.8	0.022	3.2	0.65	0-7.5
8	0.007	1.0	0.025	3.5	0.77	0-8.3
9	0.009	1.3	0.027	3.7	0.81	0-8.6
10	0.014	1.9	0.028	3.9	0.83	0-6.2
11	0.020	2.8	0.030	4.2	0.63	0-8.2
12	0.027	3.8	0.031	4.4	0.71	0-7.9
13	0.037	5.1	0.033	4.6	0.74	0-6.9
14	0.047	6.6	0.034	4.8	0.71	0-7.7
15	0.059	8.3	0.035	4.9	0.66	0-7.5
	STN = 40 pp2m		STN = 80 pp2m			
PPT15-1	0.012	1.7	0.033	4.6	-	-
2	0.008	1.2	0.026	3.7	-	-
3	0.006	0.9	0.021	3.0	-	-
4	0.005	0.7	0.017	2.4	-	-
5	0.005	0.7	0.014	1.9	-	-
6	0.005	0.8	0.011	1.6	-	-
7	0.008	1.1	0.011	1.5	-	-
8	0.011	1.6	0.011	1.6	-	-
9	0.016	2.2	0.013	1.8	-	-
10	0.021	3.0	0.015	2.1	-	-
11	0.028	3.9	0.019	2.7	-	-
12	0.036	5.0	0.024	3.4	-	-
13	0.045	6.3	0.030	4.2	-	-
14	0.055	7.7	0.037	5.2	-	-
15	0.066	9.3	0.045	6.3	-	-

[a]The PPT15-i means and ranges are listed in numerical order.

[b]Simplified derivative (dLEAFN/dPPT15-i) = C - 0.0072 PPT15-i for all levels of the interacting variables.

have little effect on water usage.

In periods 4 to 12, the PPT15 level associated with maximum LEAFN gradually increased over time at the high PLDEN level but was considerably less at the low PLDEN level (Table 28). The trend associated with the high PLDEN levels reflects the increased need for soil moisture due to increased evapotranspiration. It also reflects the need to keep the plow layer moist to increase N availability from the soil and applied sources of N because of the higher N requirements at high PLDEN levels.

In the last three periods, the greater level of PPT15 associated with maximum LEAFN at the low than at the high PLDEN level was not the expected response. The expected pattern in the period before leaf sampling was the same as had occurred in periods 4 to 12.

The first derivatives in Table 27 were next simplified for levels of STN (soil test N in the plow layer) of 40 and 80 pp2m (low and medium-high, respectively). The other interacting variables were set at: PLDEN = 375, WEEDS = 5, SAMDIF = 1, CB1 = 3, DCMAX = 54, and PLDATE = 23. The simplified derivatives as well as the values of the PPT15 indexes associated with maximum LEAFN, at both levels of STN, are shown in Table 28.

The coefficients associated with the interactions between the PPT15 indexes and STN (Table 27) indicated that higher STN levels increased the responses of LEAFN to the PPT15 indexes in periods 1 to 7 and decreased the responses of LEAFN in periods 9 to 15. As shown in Table 28, levels of PPT15 associated with maximum LEAFN were less at the low STN than at the high STN level in periods 1 to 7, but were greater at the low

STN than at high STN in periods 9 to 15. At the high level of STN, particularly, maximum LEAFN occurred at values of the PPT15 indexes much larger than their means.

In the first 7 periods, PPT15 levels above or slightly above their mean levels had negative effects on LEAFN at the low STN level while negative effects of PPT15 on LEAFN at the high STN level occurred at higher PPT15 levels. These effects showed that loss of N by leaching or denitrification caused by higher rainfall in the period of 3 to 38 days after planting had more adverse effects on LEAFN in the soils with low STN than in those with high STN which have more available mineralizable N from the soil organic matter. In the 35-day period before silking, the low STN soils needed more rainfall to attain maximum LEAFN. An increasing amount of rainfall was needed to keep the surface layer moist in order to obtain maximum availability of soil and fertilizer N in order to supply the increasing demands for water and N in the grand period of growth prior to silking. In the latest periods, only very large amounts of rainfall decreased LEAFN.

The effects of the other interacting variables on the responses of LEAFN to the PPT15 indexes, as shown in Table 27, differed somewhat in magnitude and trends over the 15 periods. The responses of LEAFN to the PPT15 indexes increased with increasing CB1 level and became larger in the later periods, i.e., higher PPT15 levels were needed to obtain maximum LEAFN as CB1 level increased. This is the expected response because corn borer damage to the conductive tissues decreases water and nutrient uptake, particularly at low soil moisture levels.

The DCMAX variable (depth to maximum clay horizon) had an unusual interaction effect with the PPT15 indexes on the LEAFN responses. It decreased the responses to these indexes the most in the 1st and 15th periods and had no effect in the 8th or middle period. The reason for this behavior is not known. Both the WEEDS and PLDATE variables had negative effects on the LEAFN responses to the PPT15 indexes which were identical in all periods (footnote, Table 27). Increasing weeds and later planting increased the adverse effects of higher PPT15 levels on LEAFN, as would be expected.

The regression coefficients of the SAMDIF interactions with the PPT15 indexes decreased linearly over the 15 periods (Table 27). During the last 7 periods, positive values of SAMDIF (sampled before silking) decreased the PPT15 level required for maximum LEAFN and negative values of it (sampled after silking) increased the PPT15 level at maximum LEAFN. These effects were similar to those of the SAMDIF*DV_i interactions on LEAFN which were shown in Table 26 and discussed previously. In the first 7 periods, however, the effects of SAMDIF were reversed because of the change in the sign of the interactions with the PPT15 indexes (Table 27). The reason for this effect is not known.

Environmental variables In this group, only the CB1 (1st-brood-corn borer) and WEEDS variables affected LEAFN in Model LEAFN-J24 (Table 23).

The linear, negative effect of CB1 on LEAFN was modified by its interactions with the 5-day PPT15 indexes, as shown by the partial derivative of dLEAFN/dCB1 = -0.0120 + 0.00107 PPT15I + 0.000197 PPT15L. These interactions between CB1 and the first-order summation variates of PPT15 showed that the coefficients of the interactions between each PPT15 index and CB1 increased linearly from negative values in the first two periods to positive values in all others, as shown in Table 27. These positive interactions showed that the negative effects of CB1 on LEAFN decreased as PPT15 increased over most of its relevant range. Because moisture and nutrient movement in the stalk is reduced by destruction of part of the conductive tissues in the lower stalk by CB1, increased moisture thus reduced these adverse effects of CB1 on LEAFN.

The effect of WEEDS on LEAFN was modified by the third-order summation variates of DV in a cubic manner over the 8 periods and by a constant negative amount by PPT15 in each period. The partial derivative is dLEAFN/dWEEDS = 0.000135 - 0.0199 DVI + 0.0164 DVL - 0.00376 DVQ + 0.000257 DVC - 0.0000464 PPT15I.

The coefficients of the DV_i*WEEDS interactions (Table 24) showed that increasing DV had negative effects on the response of LEAFN to WEEDS in periods 1, 2, 6, and 7 and positive effects in the other periods. The negative interaction effects of PPT15 decreased the rate of change of LEAFP to WEEDS in all periods. Because the small, positive coefficient of WEEDS had very little significance (t = 0.17), the WEEDS interactions with the weather indexes had the dominant effects on LEAFN. At mean values of DVI = 2.18, DVL = 11.4, DVQ = 70.47, DVC = 473.26, and PPT15I = 11.2, the simplified partial derivative = -0.000146 which showed that 100 kg/0.1 ha of air-dried weeds decreased LEAFN by about 0.015%.

<u>Tillage and planting variables</u> The PLDEN variable had a negative effect on LEAFN which was modified by its positive interactions with NBDCT and EXMO34 and by interactions with the PPT15 indexes which varied quadratically from negative in the first 3 periods to positive in the middle 9 periods and then negative in the last 3 periods (Table 27). The dLEAFN/dPLDEN = -0.00145 + 0.00000559 NBDCT + 0.000192 EXMO34 + 0.000060 PPT15I - 0.0000029 PPT15Q. At NBDCT = 125 kg N/ha, EXMO34 = 1.0 (mean = 0.42), PPT15I = 11.20 (mean), and PPT15Q = 210.80 (mean), the simplified dLEAFN/dPLDEN = -0.0005. This was a decrease of 0.05% in LEAFN per increase of 10,000 stalks per hectare.

The positive PLDEN*NBDCT interaction on LEAFN was logical because it usually affects corn yield the same way. The positive interaction between PLDEN and EXMO34 was unexpected because increased excess moisture early in the season should decrease plant-available N and increase the negative PLDEN effect on LEAFN. The negative interactions between PLDEN and these PPT15 indexes prior to silking also were unexpected because higher soil moisture levels are more necessary as PLDEN increases.

The PLDATE variable had a positive, linear effect on LEAFN (Table 23) which was modified by the negative interactions with the PPT15 indexes which were constant over all 15 periods (as determined by the PLDATE*PPT15I). The dLEAFN/dPLDATE = 0.00873 - 0.000486 PPT15I, which shows that the positive response of LEAFN to PLDATE (delayed planting) decreased as precipitation increased in each period. The earlier planted corn had lower LEAFN (perhaps a higher rate of utilization) than later planted corn. The decreased yield due to later planting thus is not related to the increased LEAFN level.

The PLOW variable (time of plowing) had a highly significant negative effect on LEAFN (dLEAFN/dPLOW = -0.044) showing that plowing in the spring reduced the LEAFN about 0.04%, on the average, as compared to plowing in the fall. Better soil physical conditions in fall-plowed soil increased N availability and LEAFN and also yields as reported by Macias-Laylle (1984).

The number of tillage operations after plowing (TILLAFT) had a quadratic effect on LEAFN (dLEAFN/dTILLAFT = 0.0327 - 0.00804 TILLAFT) which showed that maximum LEAFN occurred with 4 tillage operations. Additional tillage probably increased the compaction and decreased N availability and then LEAFN.

Likewise, the PLMETH (planting method) had a linear, positive effect on LEAFN (dLEAFN/dPLMETH = 0.04); this showed that drilled corn had about 0.04% less LEAFN than hill-dropped corn. This effect was not expected because competition for N should be less in drilled corn than in hill-dropped corn.

The new variables introduced by Macias-Laylle (1984) to account for varietal effects (HYMAT and HYCROSS) had significant effects on LEAFN (Table 23). First, the HYMAT (hybrid maturity) decreased LEAFN linearly, as shown by the dLEAFN/dHYMAT = -0.02. The late-maturing varieties had about 0.08% less LEAFN than the early ones. This may be a dilution effect because the later varieties have a larger photosynthetic apparatus and, consequently, a larger sink for storage of photosynthates, than the early maturing varieties with smaller leaf area and a smaller sink.

Hence, the N utilization efficiency (as defined by Kamprath et al., 1982) of late varieties may be higher than that of early varieties with smaller sink size, thus leading to higher LEAFN in early than in late varieties.

On the other hand, HYCROSS (coded double = 1, 3-way = 2, modified single = 3, and single = 4) had a quadratic effect on LEAFN (Table 23). The dLEAFN/dHYCROSS = -0.14 + 0.055 HYCROSS which showed that minimum LEAFN occurred at coded HYCROSS = 2.5. The curvilinear effects of this variable indicated that four-way cross and single-cross varieties had higher levels of LEAFN than 3-way and the modified single crosses. The reason for this behavior is not known but these effects may be related to the time when the 3-way, modified single, and single crosses were introduced. The first two were grown earlier in the period with the single crosses becoming the dominant varieties only in the last few years.

Fertility management variables The MANURE variable increased LEAFN slightly (Table 23). The dLEAFN/dMANURE = 0.00226 which showed that 22 MT/ha (10 T/acre) increased LEAFN by 0.05%, thus indicating that applications of manure increased N availability and LEAFN levels.

The KROW (row-applied K) variable had a quadratic effect on LEAFN, as shown by the dLEAFN/dKROW = -0.0058 + 0.00021 KROW. LEAFN decreased over most of the relevant range to a minimum at 28 kg K/ha. This response has often been reported in the literature, although no clear explanation for it has been given. It may be due to a dilution effect because of the vegetative response to KROW.

The complex relationships of the dominant variables affecting the available N for corn were shown by the effects of NBDCT and its interactions on LEAFN (Table 23). The dLEAFN/dNBDCT = 0.00461 - 0.0000216 NBDCT + 0.0000307 NCODE1 - 0.0000548 STN + 0.0000056 PLDEN + 0.0293 DVI - 0.0237 DVL + 0.00499 DVQ - 0.000309 DVC. The NBDCT had a quadratic effect on LEAFN which was positive over most of its range, a larger effect on LEAFN as corn was further removed from meadow (increased NCODE1) and as PLDEN increased, and a smaller effect as STN level increased. The interactions between NBDCT and the DV indexes varied in a cubic manner over the eight 5-day periods (Table 24). Increasing DV (less moisture stress) increased the effect of NBDCT on LEAFN in periods 1, 6, 7, and 8 and decreased the NBDCT effect in the other periods; these interactions were discussed previously in the weather index subsection.

At NCODE1 = 30 (3rd-year corn), STN = 50 pp2m (low), PLDEN = 540 or 54,000 plants/ha (about 22,000 stalks/acre), and DVI = 2.18 (mean), DVL = 11.40 (mean), DVQ = 70.47 (mean), DVC = 473.3 (mean), the simplified partial derivative = 0.00490 - 0.0000216 NBDCT. The maximum LEAFN occurred at 227 kg N/ha. The LEAFN response for these conditions then was the average slope on the response curve from 0 to 227 kg N/ha (1/2(0.00490 + 0) = 0.00245) multiplied by 227 kg N/ha, which gives 0.56% N. As the levels of the interacting variables change, the initial slopes at the intercept (at NBDCT = 0), the NBDCT levels associated with maximum LEAFN, and the magnitudes of the LEAFN responses to NBDCT all change.

The NCODE1 variable decreased LEAFN at a decreasing rate, but this curvilinear response was modified as shown by the dLEAFN/dNCODE1 = -0.0291 + 0.000690 NCODE1 + 0.000125 STN + 0.0000307 NBDCT - 0.0497 DVI + 0.0232 DVL - 0.00226 DVQ. The rate of change of LEAFN with respect to

NCODE1 became less negative as soil test N in the plow layer and applied N fertilizer increased. These responses again demonstrated the substitution effects of soil N, applied N, and legume N on LEAFN and also yield (Sridodo, 1980). The interactions between NCODE1 and the DV indexes varied quadratically over the eight 5-day periods; the responses of LEAFN to NCODE1 became more negative at higher DV levels in periods 1, 2, 3, and 8 and less negative in periods 4 to 7.

At STN = 50, NBDCT = 120, and DVI = 2.18, DVL = 11.40, and DVQ = 70.47, the simplified derivative = -0.0223 + 0.000690 NCODE1. Minimum LEAFN occurred at NCODE1 = 32.3 (closer to 3rd-year corn). The LEAFN response at these conditions from NCODE1 = 10 (1st-year corn) to 32.3 is the average slope of -0.0077 * 22.3 units = -0.17% N.

<u>Soil test variables</u> The STN variable increased LEAFN at a decreasing rate but this curvilinear response was modified by its interactions with NCODE1, NBDCT, and the PPT15 indexes (Table 23). As expected, the response of LEAFN to soil N increased as NCODE1 increased and decreased as NBDCT increased, as shown by the dLEAFN/dSTN = 0.0167 - 0.000197 STN + 0.000125 NCODE1 - 0.0000548 NBDCT - 0.0000751 PPT15L. The interactions between STN and each of the PPT15 indexes (Table 27) showed that the response of LEAFN to STN increased as precipitation increased in periods 1 to 7 and the opposite response was observed in periods 9 to 15. This interaction has been discussed in regard to the effects of the PPT15 indexes on LEAFN.

The STN variable only interacted with the PPT15 indexes and not with the DV indexes. This seems to confirm the assumption that the

PPT15 (rainfall) indexes affect the availability of N in the plow layer while the DV (moisture stress) indexes influence the availability of N throughout the soil profile as well as the physiological effects of moisture stress on nutrient uptake and translocation within the corn plants.

Soil test K (STK1) had a linear, positive effect on LEAFN (dLEAFN/dSTK1 = 0.000183). However, it was not clear in this study why higher levels of applied row K decreased LEAFN while higher soil test K levels increased it.

Soil variables The THAHOR variable had a negative, linear effect on LEAFN which was modified by interactions with the quadratic function of the DV summation variates (Table 23). The dLEAFN/dTHAHOR = -0.00243 + 0.0396 DVI - 0.0170 DVL + 0.00155 DVQ. As shown in Table 24, the coefficients of the interactions between THAHOR and DV varied in a quadratic manner from positive in the first 3 periods to negative in the next 4 periods and then negative in the last period. Increasing THAHOR had a net negative change on LEAFN in all periods except in the first one.

The effect of THAHOR on LEAFN was expected to be positive because of the high correlation of r = 0.70 between THAHOR and % organic carbon in the 0-51 cm layer (Sridodo, 1980). However, the THAHOR effect in this study may be reflecting the soil drainage class effect on LEAFN because of the moderate r = 0.44 between THAHOR and DRAIN. The organic matter effect on LEAFN probably is being expressed more through the STN than the THAHOR variable.

The DCMAX (depth to maximum clay) variable had a positive, linear effect on LEAFN which was modified by interactions with the PPT15 and EXMO34 indexes (Table 23), as shown by dLEAFN/dDCMAX = 0.00174 - 0.0000057 PPT15Q + 0.00102 EXMO34. The negative interactions between DCMAX and the PPT15 indexes (Table 27) showed that increasing PPT15 decreased the positive response of LEAFN to DCMAX in a quadratic manner over the 15 periods. Increasing EXMO34 (excess moisture index in the period of 19 to 35 days after planting) had a positive effect on the LEAFN response to DCMAX. The contrasting effects of the two weather indexes may reflect some intercorrelation between the PPT15 and EXMO34 indexes not detected by simple correlation.

The DCMAX effect on LEAFN is difficult to interpret because it probably includes indirect effects of several other variables. Although it has no moderate or high simple correlations with other soil variables, it is intercorrelated with slope, erosion class, THAHOR, drainage class, CPL, RANGE (E-W location), and alluvial soils, as shown by latent roots and vectors analysis (Pena-Olvera, 1979).

The CPL (% clay in the plow layer) variable had a quadratic effect on LEAFN. From the dLEAFN/dCPL = 0.0061 - 0.00032 CPL, maximum LEAFN occurred at 19% clay (a light silt loam or loam). Its effect on LEAFN may reflect its correlations with DRAIN ($r = 0.48$) and CMAX or maximum clay in the subsoil ($r = 0.67$) and their effects on N availability and N losses by leaching and denitrification. At clay levels less than 19%, soil texture becomes a coarse silt loam, a light loam, or a sandy loam and then a loamy sand in which leaching losses of N increase. At clay levels above 27%, soil texture becomes a silty clay loam or clay loam and then a silty clay, clay, or sandy clay, the CMAX increases, soil drainage becomes poorer, N losses by denitrification increase, and mineralization of N from organic matter decreases.

All other soil and location variables had only linear effects on LEAFN (Table 23). The partial derivatives of LEAFN with respect to BIO, DCAL, TILL, PALEO, ALLUV, and TWP were 0.016, -0.00059, -0.05, -0.16, -0.06, and 0.004, respectively. These average effects show that LEAFN increased 0.06% as BIO changed from forest to prairie, decreased from 0 to 0.08% as DCAL (decoded depth to carbonate horizon) varied from 152 to 15 cm (60 to 6 in.), decreased 0.05%, 0.16%, and 0.06% in till-derived soils, paleosols, and alluvium, respectively, as compared to deep loess-derived soils, and increased 0.13% from southern to northern Iowa. All of these effects were as expected.

<u>Time of sampling variable</u> The SAMDIF (difference between silking and sampling dates in which positive and negative values show sampling prior to and after silking, respectively) had a quadratic effect on LEAFN which was modified by its interactions with the DV and PPT15 indexes. The dLEAFN/dSAMDIF = 0.0472 - 0.01284 SAMDIF - 0.108 DVI + 0.0171 DVL - 0.000467 PPT15L. The interactions between SAMDIF and DV (Table 24) showed that increasing DV (better moisture conditions) decreased the rate of change of LEAFN to SAMDIF in the first 6 periods and had the opposite effect in the last 2 periods. Those between SAMDIF and the PPT15 indexes (Table 27) showed that increasing PPT15 increased the rate of change of LEAFN to SAMDIF in the first 7 periods and decreased the LEAFN response in the last 7 periods.

At mean values of DVI = 2.18, DVL = 11.40, and PPT15L = -2.36, the simplified derivative = 0.0078 - 0.01284·SAMDIF. The maximum LEAFN occurred at SAMDIF = 0.6 or 0.6 day before the silking date. If leaf sampled 4 days before or after the date of maximum LEAFN, the LEAFN will be about 0.10% N less. The effects of the weather variables will be to increase or decrease the LEAFN responses to SAMDIF and to shift the SAMDIF associated with maximum LEAFN. The weather effects are complex as discussed in the previous paragraph.

Corn Leaf P Concentration

The purpose of this section was to determine the relationships between the corn leaf P concentration (LEAFP) and weather factors and their variability throughout the growing season, as well as with some soil and management factors.

First, some weather indexes computed for various periods of the growing season or small subdivisions of some periods were evaluated by the simple correlations between them and LEAFP. Second, a base model of LEAFP on selected soil and management variables was developed to further evaluate the selected weather indexes and to quantify the relationships between LEAFP and selected soil and management factors. After the base model was computed and the weather indexes were selected, interactions between weather factors and some soil or management variables were assessed as well as some interactions between variables of the soil and management group. Lastly, the final interaction model for LEAFP was discussed.

Correlation analysis of weather indexes

Excess moisture, moisture stress, and precipitation indexes were investigated to relate soil moisture conditions and meteorological factors and their variability during the growing season to LEAFP. Procedures used for this testing were similar to those used for LEAFN.

During the first stage of this testing, the five moisture stress indexes in the soil moisture program and the weighted and unweighted precipitation indexes computed for four periods of the growing season, as well as the EXMO and PPT46 indexes, were correlated with LEAFP. The simple correlation coefficients between these indexes and LEAFP are presented in Table 29.

The correlations between the weather indexes within the same period were examined in the LEAFN section (Table 4). Hence, only the correlations between these indexes and LEAFP will be discussed here.

The simple correlation coefficients given in Table 29 revealed that the associations between these indexes and LEAFP were similar to those between the same indexes and LEAFN (Table 4). That is, the DT and DW indexes showed similar coefficients with LEAFP in each of the four periods as did the DV and X1 indexes, thus showing the very high correlations between these pairs of indexes. The high correlations between the weighted and unweighted precipitation indexes also resulted in similar correlation coefficients with LEAFP.

The correlations between LEAFP and the moisture stress indexes of DX75, DV75, and X175 were surprisingly higher ($r = 0.163$, 0.178, and 0.180, respectively) than those between LEAFP and any moisture stress

Table 29. Simple correlation coefficients between LEAFP and weather indexes for various periods of the growing season

Weather index[a]	r-value	Weather index	r-value	Weather index	r-value
DT75	.139	DV40	.126	DTB	.146
DX75	.163	X140	.132	DXB	.131
DW75	.141	PPT40	.212	DWB	.143
DV75	.178	PPT40W	.230	DVB	.136
X175	.180			X1B	.136
PPT75	.162	DTA	.061	PPTB	.197
PPT75W	.179	DXA	.012	PPTBW	.199
		DWA	.074		
DT40	.126	DVA	.024	EXMO	-.136
DX40	.085	X1A	.033	PPT46	.129
DW40	.139	PPTA	.101		
		PPTAW	.106		

[a]The identification of these weather indexes and the times of the periods of the growing season are given in Table 2.

index in any other period (Table 29). The correlations between the stress indexes and LEAFP decreased moderately in the 40-day period before leaf sampling compared with the 75-day period. Within the two subdivisions of the 40-day period, the coefficients between these indexes and LEAFP in period B (22 to 2 days before leaf sampling) were similar to those for the whole 40-day period while those for the period A (42 to 22 days before leaf sampling) were much less.

A comparison of the DV and X1 indexes against the DT and DW indexes in the four periods showed that the former two were more correlated with LEAFP than the latter two in the 75-day period, were about the same in the 40-day period, but were slightly lower in period B. On the average, the growth stage weighting (DW vs DT), energy weighting (DX vs DT), or weighting by both growth stage and energy (DV or X1 vs DT) had little effect on the correlations with LEAFP except in the 75-day period (Table 29).

The correlations between LEAFP and the two precipitation indexes were highest in the 40-day period, decreased slightly in period B and again in the 75-day period, and were the least in period A. Except in the 75-day period, these indexes were more correlated with LEAFP than any of the moisture stress indexes. In general, rainfall occurring prior to the time of sampling was more associated with LEAFP than the rainfall accumulated over longer periods.

The EXMO index showed a negative association with LEAFP ($r = -0.136$), but the rainfall (PPT46) corresponding to the same period showed a slightly lower, but unexpectedly positive, correlation with LEAFP.

Based on this preliminary correlation analysis, the moisture stress indexes of DV75, DV40, DVA, DVB, and DT40 and the precipitation indexes of PPT40, PPTA, and PPTB, as well as the EXMO index, were retained to be tested in alternative regression models. A new precipitation index designated as PPT32, which represented the rainfall accumulated for 32 days starting 3 days after planting, was included instead of the PPT46 index. This was done to reduce its intercorrelation with the PPT40 index so that both indexes could be tested in the same regression model.

As was done in the LEAFN section, the 40-day period before sampling was subdivided into eight 5-day intervals and the 5 moisture stress and the 2 precipitation indexes were accordingly computed. Similarly, six

8-day excess moisture and four 8-day precipitation indexes were computed for the 48-day and 32-day periods starting 3 days after the planting date. All of these indexes were correlated with LEAFP to ascertain the association between the variability in the weather conditions and LEAFP.

The simple correlation coefficients between LEAFP and the moisture stress, precipitation, and excess moisture indexes are given in Table 30. The high intercorrelations between DT and DW, DV, DX, and X1, and between the two precipitation indexes were manifested by their similar correlation coefficients with LEAFP. Therefore, only one index from each group of highly correlated indexes should be retained for further testing. However, the correlations among the eight DT, DV, or PPT indexes (Table 6) showed that the DT indexes were highly correlated, the DV indexes were moderately correlated, and the PPT indexes were not correlated. Therefore, only the relationship between LEAFP and the eight 5-day DV and PPT indexes will be further investigated.

The negative correlation in Table 30 between DV1 and LEAFP ($r = -0.13$) showed that LEAFP decreased as soil moisture increased (less moisture stress). This relationship then became positive from the third period on and showed that higher LEAFP was associated with an increase in DV (higher soil moisture).

On the other hand, the correlation coefficients between LEAFP and the PPT indexes revealed that LEAFP was not correlated with PPT1 but was positively correlated with the other seven PPT indexes. Higher levels of LEAFP corresponded to higher amounts of rainfall in these periods.

The simple correlation coefficients between LEAFP and the six 8-day

Table 30. Simple correlation coefficients between LEAFP and weather indexes computed for 5-day and 8-day periods

	Period[a]							
Index	1	2	3	4	5	6	7	8
DT	-.02	.03	.07	.11	.15	.12	.13	.12
DX	-.13	-.03	.08	.06	.09	.05	.08	.15
DW	-.03	.03	.07	.11	.15	.12	.13	.12
DV	-.13	-.03	.08	.06	.09	.05	.08	.15
X1	-.13	-.02	.08	.06	.09	.05	.09	.15
PPT	.01	.08	.07	.05	.06	.10	.12	.12
PPTW	.01	.07	.07	.05	.06	.10	.12	.12
EXMO	-.04	-.10	-.12	-.10	-.09	-.07	-	-
PPTEM	.03	-.02	-.03	-.03	-	-	-	-

[a]The DT, DX, DW, DV, X1, PPT, and PPTW were computed for the eight 5-day periods in the 40-day period before leaf sampling date, while the EXMO and PPTEM indexes were computed for six and four 8-day periods in the period starting 3 days after planting date.

excess moisture indexes (EXMO1 to EXMO6) showed that the highest negative correlations occurred in periods 2 to 5 which suggested that excess moisture conditions from about 11 to 43 days after emergence decreased P uptake and LEAFP at sampling time. However, rainfall occurring during the first four periods had no significant effects on LEAFP (Table 30).

Development of the base regression model

A base quadratic model of LEAFP on selected soil and management variables was computed to test further the selected weather indexes or selected combinations of them. The procedures used to develop this model were the same as those used in the LEAFN section. The variables utilized are given in Table 1 and their means and ranges are listed in Appendix Table A4.

Correlation analysis   Because the variables employed to develop the base model for LEAFP were the same ones used for the LEAFN base model, the correlations between pairs of soil and management variables are also the same as given in Table 8.

A series of alternative models of LEAFP on the linear functions of these variables were computed to select from the pairs of highly correlated variables the ones that gave the higher R^2. In this manner, the deleted variables from the fertility management group were KBDCT, NRES1, and KRES1. Because the linear regressions gave no definite indication as to which of the three row-applied fertilizer variables (NROW, PROW, and KROW) to retain, they were kept for further testing in alternative quadratic regression models.

The correlations between EROS and THAHOR, CPL and CMAX, DCAL and PHMIN, and STK1 and STK2 were evaluated in a similar manner and the EROS, CMAX, PHMIN, and STK2 variables were deleted. The highly correlated PAWC and SAND variables were still retained for subsequent evaluation. The RL3, SL1, and CB2 variables were also deleted for the same reasons given in the LEAFN section.

Model selection   A series of regressions of LEAFP on linear and squared functions of selected soil and management variables were computed to determine the most significant terms and to evaluate further the pairs of highly correlated variables still present in the model. This was designated as the Model LEAFP-A series and the variates included are listed in Table 31. A total of 50 linear variates along with 43 squared variates were included in the initial model. A stepwise, backward elimination procedure was applied to delete the nonsignificant variates at the 10% level; however, a linear variate was retained regardless of its significance if its squared variate was significant.

The model selection steps followed are outlined in Table 32. The complete regression model of LEAFP on all 93 variates attained a R^2 of 0.460. Deletion of 41 nonsignificant variates stepwise reduced the R^2 of Model LEAFP-A8 to 0.453.

Deleting the variates of the highly significant, but difficult to interpret, BARR variable in Model LEAFP-A9 decreased the R^2 only 3.2%, which is a rather small amount compared to the 10% reduction observed in the case of LEAFN. This suggests that the BARR variable is less related to factors involved in the LEAFP levels than with those determining the levels of LEAFN.

Alternative Models LEAFP-A10 to -A13 were computed to test the highly correlated PROW and KROW variables; the highly correlated NROW variable had been deleted previously. Both variables were deleted because of nonsignificance. In Models LEAFP-A14 to -A19, more nonsignificant variables were deleted with a slight reduction in the R^2.

At this point, the models still contained the quadratic functions of the DV75 and EXMO indexes. Because the purpose of this section was to develop a base model for the testing of selected weather indexes, these variates were deleted and Model LEAFP-A20 was computed. Deletion of these variates decreased the R^2 from 0.413 to 0.370 in Model LEAFP-A20,

Table 31. Variates included in the base regression Model LEAFP-A series

X_i [a]	Variate	X_i	Variate	X_i	Variate
3	LEAFP	35	PAWC	67	$ROWWID^2$
5	PLDEN	36	NCODE1	68	$MANURE^2$
6	BARR	37	HYMAT	69	$NROW^2$
7	CRW	38	HYCROSS	70	$PROW^2$
8	CB1			71	$KROW^2$
9	WEEDS	39	TWP	72	$NBDCT^2$
10	CULT	40	RANGE	73	$PBDCT^2$
11	PLOW			74	$TILE^2$
12	TILLAFT	41	THAHOR	75	$PRES1^2$
13	PLDATE	42	DRAIN	76	$PRES2^2$
		43	CPL	77	$PRES3^2$
15	PLMETH	44	DCMAX	78	$SLOPE^2$
16	ROWWID	45	BIO	79	$ROWSLP^2$
17	MANURE			80	$PH1^2$
18	NROW	46	LOESS/T	81	STN^2
19	PROW	47	TILL	82	$STP1^2$
20	KROW	48	PALEO	83	$STK1^2$
21	NBDCT	49	SAND	84	$DV75^2$
22	PBDCT	50	COLLUV	85	$EXMO^2$
		51	ALLUV	86	$PAWC^2$
23	TILE			87	$NCODE1^2$
24	PRES1	52	DPHMIN	88	$HYMAT^2$
25	PRES2	53	DCAL	89	$HYCROSS^2$
26	PRES3	54	STP2	90	TWP^2
		55	SAMDIF	91	$RANGE^2$
27	SLOPE			92	$THAHOR^2$
28	ROWSLP	58	$PLDEN^2$	93	$DRAIN^2$
		59	$BARR^2$	94	CPL^2
29	PH1	60	CRW^2	95	$DCMAX^2$
30	STN	61	$CB1^2$	96	BIO^2
31	STP1	62	$WEEDS^2$	97	$DPHMIN^2$
32	STK1	63	$CULT^2$	98	$DCAL^2$
		64	$PLOW^2$	99	STP^2
33	DV75	65	$TILLAFT^2$	100	$SAMDIF^2$
34	EXMO	66	$PLDATE^2$		

[a]Refers to the position of the variate in the data set.

Table 32. Model selection steps to derive the base model for LEAFP, Model LEAFP-A series

Model no.	No. of variates	Identification	R^2
LEAFP-A1	93	Complete model, all variates listed in Table 31	.460
A2 to A8	85 to 52	Deleted 41 nonsignificant linear and squared variates stepwise from Model LEAFP-A1	.460 to .453
A9	50	Deleted BARR and $BARR^2$	.421
A10 to A13	48 to 46	Deleted PROW, $PROW^2$, KROW, and $KROW^2$ after testing in alternative models	.420 to .417
A14 to A19	45 to 40	Deleted 6 nonsignificant variates stepwise	.416 to .413
A20	36	Final model, deleted DV75, $DV75^2$, EXMO, and $EXMO^2$	.370

thus indicating that these two indexes explained about 4.3% of the variability in LEAFP. This final model was regarded as the base model for LEAFP and its regression statistics are given in Table 33.

Testing of weather indexes

This testing consisted of three stages. The first one included the evaluation of selected weather indexes for the four periods of 75 days, 40 days prior to leaf sampling, and the two halves of the 40-day period. In the second stage, the eight 5-day DV and PPT indexes, the six 8-day

Table 33. Regression statistics of the base model of LEAFP on selected variates, Model LEAFP-A20[a]

X_i	Variate	b_i	X_i	Variate	b_i
5	PLDEN	-0.000257**	50	COLLUV	0.0101++
10	CULT	-0.00524	51	ALLUV	0.00732*
11	PLOW	-0.00231			
13	PLDATE	0.000119	53	DCAL	0.0000241
			54	STP2	0.000167**
17	MANURE	0.000248**	55	SAMDIF	-0.00190**
21	NBDCT	0.000131**			
22	PBDCT	0.000360*	58	$PLDEN^2$	0.000000209*
24	PRES1	0.000279*	63	$CULT^2$	0.00108*
25	PRES2	0.000412**	72	$NBDCT^2$	-0.000000371++
			73	$PBDCT^2$	-0.00000579
29	PH1	0.00397**	75	$PRES1^2$	-0.00000386++
30	STN	0.00195**	76	$PRES2^2$	-0.00000621**
31	STP1	0.00101**	80	$PH1^2$	-0.0000809**
			81	STN^2	-0.0000117**
36	NCODE1	-0.00300**	82	$STP1^2$	-0.00000356**
38	HYCROSS	-0.0178**	87	$NCODE1^2$	0.0000493**
41	THAHOR	0.000736**	89	$HYCROSS^2$	0.00284*
			92	$THAHOR^2$	-0.0000103**
48	PALEO	-0.0271**	98	$DCAL^2$	-0.00000151*
49	SAND	0.0112**	100	$SAMDIF^2$	-0.000740**

[a]Intercept = 0.243**, R^2 = 0.370, and no. of variates = 36.

excess moisture, and the four 8-day PPTEM indexes were tested. In the third stage, the summation variates of the 5-day PPT, PPT15, and DV indexes were evaluated. In each stage, the respective indexes were added to the base model either individually or in selected combinations and their relevance to LEAFP was evaluated in terms of the improvement of the R^2 of the resulting regressions.

<u>First stage of testing</u> Indexes tested in the first stage were the moisture stress indexes of DV75, DV40, DT40, DVA, and DVB, the precipitation indexes of PPT40, PPTA, PPTB, and PPT32, and the excess moisture index of EXMO. They were added to the base model in such a way so that the effect of an index or a selected combination of indexes could be ascertained by the improvement in the explained variability in LEAFP. These regressions were designated as the Model LEAFP-B series; a description and R^2-values of the alternative models are given in Table 34.

Models LEAFP-B1 to -B4 showed that the EXMO index increased the R^2 very little (+0.7%), but DV75 gave a substantial improvement in R^2 (+3.7%) and the combination had an additive effect on the R^2 (+4.4%). In Models LEAFP-B5 to -B7, DV40, the energy and growth stage weighted stress index, gave a slightly better R^2 than DT40, the unweighted index. However, PPT40, the precipitation index for the same period, gave an R^2 that was about 2% higher than that of models with either DV40 or DT40.

The effects of partitioning the DV40 and PPT40 periods into two 20-day periods are observed in Models LEAFP-B9 to -B12. Both DVB and PPTB indexes for the 20-day period just before leaf sampling explained more variability in LEAFP than the DVA and PPTA indexes for the 42 to 22 days before the leaf sampling date. Inclusion of the PPT32 with the EXMO index in Model LEAFP-B8 did not increase the R^2. Substitution of PPT32 for EXMO in Models LEAFP-B13 to -B16 reduced slightly the R^2 in all comparisons. Hence, PPT32 was dropped from any further testing.

A comparison of the DV indexes in Models LEAFP-B4, -B5, -B9, and -B10 in Table 34 showed that DV75 attained the highest R^2, DV40 and DVB

Table 34. R^2-values of the alternative regressions of LEAFP on the base model and selected weather indexes, Model LEAFP-B series

Model no.	Variables[a]	R^2
LEAFP-B1	Base model[b]	.370
B2	Base model + EXMO	.377
B3	+ DV75	.407
B4	+ EXMO + DV75	.413
B5	+ EXMO + DV40	.400
B6	+ EXMO + DT40	.397
B7	+ EXMO + PPT40	.419
B8	+ EXMO + PPT32	.378
B9	+ EXMO + DVA	.382
B10	+ EXMO + DVB	.402
B11	+ EXMO + PPTA	.385
B12	+ EXMO + PPTB	.413
B13	+ PPT32 + DV40	.394
B14	+ PPT32 + PPT40	.412
B15	+ PPT32 + DVB	.394
B16	+ PPT32 + PPTB	.409
B17	+ EXMO + PPT40 + DV40	.427
B18	+ EXMO + PPTB + DVB	.427
B19	+ EXMO + PPTA + DVA	.390
B20	+ EXMO + PPTA + DVA + PPTB + DVB	.433

[a]The models included quadratic functions of the weather indexes.

[b]Base model was Model LEAFP-A20 (Table 33) with 36 variates and $R^2 = 0.370$.

had about equal precision for predicting LEAFP, and DVA had the lowest R^2. The similar effects of DV40 and DVB suggested that soil moisture conditions prevailing just prior to the time of sampling explained about as much variability in LEAFP as soil moisture conditions of even earlier periods. Surprisingly, soil moisture conditions after sampling increased the R^2 as shown by the effect of DV75 on predicting LEAFP. This effect, however, may be a delayed or lagged one because moisture stress, as computed by the DV variable, develops usually after a period of low antecedent precipitation.

Likewise, comparison of the PPT indexes in Models LEAFP-B7, -B11, and -B12 showed that PPT40 gave the highest R^2 (0.419), which was slightly higher than that of PPTB (0.413) and considerably higher than the R^2 of PPTA (0.385). The R^2-values of PPT40 and PPTB were higher than those of the stress indexes for the same periods. Therefore, these suggested that rainfall occurring in the 20-day or 40-day period before leaf sampling explained as much or more variability in LEAFP than the complex moisture stress indexes computed for similar or longer periods.

Because the moisture stress and precipitation indexes for the same periods prior to leaf sampling were only slightly correlated, they could be combined along with the EXMO index in Models LEAFP-B17 to -B20 (Table 34). The indexes for period A were the least associated with LEAFP variability, whereas the indexes for period B gave the same R^2 as the 40-day indexes, again showing that moisture conditions just before sampling time were more related to the variability of LEAFP than other times.

The inclusion of both precipitation and moisture stress indexes for the same period in the same regression produced R^2-values that were larger than those obtained with either index alone, demonstrating that both indexes were representing different sources of variability on LEAFP. Lastly, Model LEAFP-B20 included the moisture stress and precipitation indexes for both periods A and B. Its R^2 was slightly higher than the R^2 of models containing only the indexes for one period.

<u>Second stage of testing</u> The PPT and DV indexes that were computed for the eight 5-day periods in the 40-day period before leaf sampling as well as the early season 8-day excess moisture and precipitation indexes were evaluated as to the improvement of the R^2 when added either individually or in selected combinations to the base model of LEAFP. These alternative regression models were designated as the Model LEAFP-C series. Table 35 shows the weather indexes that were included in each alternative model as well as their respective R^2-values.

A comparison of Models LEAFP-C1 to -C4 revealed that the quadratic functions of the 5-day PPT and DV indexes increased the R^2-values above those for their respective linear functions. Likewise, models including either the PPT or the DV indexes gave almost identical increases in R^2-values of about 5%, thus indicating that both indexes explained about the same variability in LEAFP. The combination of the PPT and DV indexes in Model LEAFP-C5 gave a further increase in R^2 of about 4%. The R^2 of 0.458 of this model was an increase of 8.8% above that of the base model and a 3.1% increase above the R^2 of Model LEAFP-B17 (Table 34) containing the EXMO, PPT40, and DV40 indexes. Therefore, the 5-day PPT and DV

Table 35. R^2-values of the alternative regressions of LEAFP on the base model and selected weather indexes, Model LEAFP-C series

Model no.	Variables (base model plus following weather variables)[a]	No. of weather variates	R^2
LEAFP-C1	PPT1 to PPT8 (linear variates, only)	8	.408
C2	PPT1 to PPT8	16	.420
C3	DV1 to DV8 (linear variates, only)	8	.412
C4	DV1 to DV8	16	.419
C5	PPT1 to PPT8 + DV1 to DV8	32	.458
C6	PPTEM1 to PPTEM4	8	.377
C7	EXMO1 to EXMO6	12	.384
C8	PPTEM1 to PPTEM4 + EXMO1 to EXMO6	20	.389
C9	PPT1 to PPT8 + PPTEM1 to PPTEM4	24	.426
C10	PPT1 to PPT8 + EXMO1 to EXMO6	28	.431
C11	PPT1 to PPT8 + PPTEM1 to PPTEM4 + EXMO1 to EXMO6	36	.436
C12	DV1 to DV8 + PPTEM1 to PPTEM4	24	.429
C13	DV1 to DV8 + EXMO1 to EXMO6	28	.435
C14	DV1 to DV8 + PPTEM1 to PPTEM4 + EXMO1 to EXMO6	36	.441
C15	PPT1 to PPT8 + DV1 to DV8 + PPTEM1 to PPTEM4	40	.464
C16	PPT1 to PPT8 + DV1 to DV8 + EXMO1 to EXMO6	44	.469
C17	PPT1 to PPT8 + DV1 to DV8 + PPTEM1 to PPTEM4 + EXMO1 to EXMO6	52	.473
C18	Reduced model, deleted nonsignificant variates from Model LEAFP-C17	27	.466

[a]Except where indicated, models included quadratic functions of the weather indexes; base model was LEAFP-A20 (Table 33) with 36 variates and R^2 = 0.370.

indexes are representing factors that exert different effects on LEAFP.

In Models LEAFP-C6 to -C17 (Table 35), addition of the 6 excess moisture indexes and the 4 PPTEM indexes either alone, together, or in various combinations with the PPT and DV indexes gave only slight increases in R^2. The 6 excess moisture indexes gave slightly larger increases in the R^2-values than the 4 PPTEM indexes.

The R^2-values of the DV indexes in these models were similar to those of the PPT indexes. In the previous series, the precipitation indexes increased the R^2 slightly more than the moisture stress indexes.

At this point, the significant effects of the 5-day and 8-day weather indexes on LEAFP were determined. From Model LEAFP-C17, which included the four types of indexes that described the diverse effects of various weather factors on LEAFP from 3 days after planting to 2 days before the sampling date, nonsignificant variates were deleted by stepwise, backward elimination. The regression statistics of the resulting Model LEAFP-C18 are given in Table 36.

Examination of Model LEAFP-C18 showed that the excess moisture conditions occurring in the second, third, and fourth 8-day periods exerted negative effects on LEAFP. EXMO3 decreased LEAFP at a decreasing rate and reached a minimum at EXMO3 = 1.45, much larger than its mean value. The precipitation indexes for the first three 8-day periods also had negative effects on LEAFP, with the first two PPTEM indexes decreasing LEAFP at decreasing rates and attaining minimum values at PPTEM1 = 1.87 and PPTEM2 = 2.10, both considerably higher than their means of about 1.2. Higher values of these PPTEM indexes then increased LEAFP.

Table 36. Regression statistics of the selected weather indexes in reduced Model LEAFP-C18[a]

Variable[b]	b_i Linear	b_i Squared	Quadratic effect[c]
EXMO2	-0.00367**	-	-
EXMO3	-0.00886**	0.00306**	MIN at 1.45
EXMO4	-0.00389*	-	-
DV1	-0.783**	2.186**	MIN at 0.18
DV3	0.0774**	-	-
DV4	0.246**	-0.451*	MAX at 0.27
DV5	0.0498**	-	-
DV8	0.0324**	-	-
PPTEM1	-0.00213	0.000572++	MIN at 1.87
PPTEM2	-0.00299*	0.000708*	MIN at 2.10
PPTEM3	-0.00111++	-	-
PPT1	-0.00150++	-	-
PPT3	0.00555**	-0.00104*	MAX at 2.67
PPT4	0.00179*	-	-
PPT5	0.00573**	-0.00108*	MAX at 2.65
PPT6	0.00670**	-0.000794++	MAX at 4.24
PPT7	0.00948**	-0.00129**	MAX at 3.67
PPT8	0.00275**	-	-

[a]Intercept = 0.200**, R^2 = 0.466, and no. of variates = 63.

[b]Means and ranges of the weather indexes are given in Appendix Table A3.

[c]Value of the weather index associated with minimum (MIN) or maximum (MAX) LEAFP.

The negative effects of severe excess moisture conditions on P uptake were attributed by Lal and Taylor (1970) to factors such as soil reducing conditions leading to increased solubility of heavy metals like Al, Fe, and Mo which tend to form insoluble P compounds. These authors also pointed out that some other factors such as a limited root system, excess of CO_2 causing suberization of root hairs, and inadequate aeration may inhibit nutrient uptake and its translocation within the plant. Hence, one or more of these factors could contribute to the negative responses of LEAFP to increasing levels of the excess moisture and early - season precipitation indexes. Also, in these data, some effects of early-season excess moisture on LEAFP may be indirect through its correlation with LEAFN ($r = 0.57$) which had responded negatively to the EXMO and PPTEM indexes (Table 15).

Five of the 5-day DV indexes had significant effects on LEAFP (Table 36). An increase in DV1 (higher soil moisture) decreased LEAFP at a decreasing rate and it reached a minimum at DV1 = 0.18, a value slightly less than the upper range of observed values. This response to an increasing DV1 level was very similar to the LEAFN response to DV1. The lack of significance of DV2 revealed that a transition from a situation of excess moisture to a situation of soil moisture deficits was occurring in period 2 because DV3, DV4, and DV5 indexes had positive effects on LEAFP. Only DV4 showed a curvilinear effect on LEAFP which was at its maximum at DV4 = 0.27; then higher DV4 values decreased LEAFP. The DV6 and DV7 indexes had no significant effect on LEAFP but DV8 had a positive, linear effect.

Therefore, the DV3 to DV8 indexes indicated that when increasing moisture stress dries the plow layer, which usually has higher available P than the subsurface layers, the subsequent reduction in P uptake is ultimately reflected in lower LEAFP at the leaf sampling time. The negative effects of decreased soil moisture on leaf P have been reported by Dumenil and Hanway (1965), Voss (1962, 1969), Miranda (1981), and Estrella-Chulin (1984).

The effects of the 5-day PPT indexes on LEAFP were similar to those of the DV indexes (Table 36). The PPT1 index also had a negative effect on LEAFP. Conversely, the PPT3 to PPT8 indexes all had positive effects on LEAFP in most of their relevant ranges. The PPT3, PPT5, PPT6, and PPT7 indexes had curvilinear effects on LEAFP with maximum levels of LEAFP occurring at PPT3 = 2.67, PPT5 = 2.65, PPT6 = 4.24, and PPT7 = 3.67. These effects indicated that increasing PPT first increased LEAFP, probably because of increased P availability in the more moist soil plow layer; higher amounts of rainfall, however, decreased LEAFP, probably indirectly because the excess moisture conditions also decreased LEAFN (Table 15).

Third stage of testing   Next, the summation variates of a third-order polynomial of the linear and squared functions of the 5-day PPT, PPT15, and DV indexes as well as those for the PPT*DV interactions were evaluated by a procedure similar to that applied in the LEAFN section.

The summation variates of the PPT, PPT15, and DV indexes were added either individually or combined to the base model and were evaluated by their effects on the R^2. This series was designated as the Model LEAFP-D series and Table 37 presents the indexes included in each regression and their respective R^2-values.

Models LEAFP-D1 to -D4 (Table 37) showed that the quadratic functions of the PPT and DV indexes had similar effects on LEAFP by increasing the R^2 almost the same. The quadratic functions of both were slightly better for predicting LEAFP than their linear functions.

Combination of the PPT and DV summation variates in Model LEAFP-D5 increased the R^2 about 4% with respect to the models including only the summation variates of each index. The addition of the variates representing the interactions between these indexes had no effect on the R^2 (Model LEAFP-D6).

Alternative Models LEAFP-D7 to -D11 in Table 37 showed that the inclusion of seven additional 5-day precipitation indexes had a slight effect on the R^2. Addition of the EXMO index resulted in only slight increases in the R^2, whereas the addition of the PPT32 index had no effect on the R^2.

To ascertain if the summation technique was useful to estimate the responses of LEAFP to the 5-day PPT and DV indexes, the rates of change of LEAFP with respect to each 5-day index were calculated in a fashion similar to that in the LEAFN section. That is, the first derivatives of LEAFP with respect to each 5-day PPT or DV index were calculated from the directly observed regression coefficients in Model LEAFP-C5, and from the regression coefficients estimated from the summation variates of these indexes in Model LEAFP-D5. Then, the rates of change of LEAFP with respect to each 5-day index were calculated by substituting the average

Table 37. R^2-values of the alternative regression models of LEAFP on the summation variates of a third-order polynomial of the 5-day DV, PPT, and PPT15 indexes and other indexes, Model LEAFP-D series

Model no.	Variable (base model plus following weather variables)[a]	No. of weather variates	R^2
LEAFP-D1	LPPT	4	.405
D2	LPPT + QPPT	8	.414
D3	LDV	4	.410
D4	LDV + QDV	8	.415
D5	LPPT + QPPT + LDV + QDV	16	.452
D6	LPPT + QPPT + LDV + QDV + IPPT	20	.452
D7	LPPT + QPPT + LDV + QDV + IPPTDV + EXMO	22	.458
D8	LPPT + QPPT + LDV + QDV + IPPTDV + EXMO + PPT32	24	.458
D9	LPPT15 + QPPT15	8	.416
D10	LPPT15 + QPPT15 + LDV + QDV	16	.453
D11	LPPT15 + QPPT15 + LDV + QDV + EXMO	18	.457
D12	Reduced model, deleted nonsignificant variates from Model LEAFP-D5	11	.450

[a]Symbols of summation variates are described in Table 3; L, Q, and I are the four summation variates of a third-order polynomial representing the linear, squared, and interaction functions of the 5-day weather indexes, respectively; base model was Model LEAFP-A20 (Table 33) with 36 variates and R^2 = 0.370.

values of each index in their respective derivatives.

Figure 5 presents the rates of change of LEAFP with respect to each DV index that were calculated from the estimated (dashed line) and from the directly observed (solid line) regression coefficients. It can be observed that the rates of change in LEAFP calculated from the summation variates fit with a high degree of precision the rates obtained from the directly observed coefficients. The rates of change of LEAFP in Figure 5 showed the same pattern as the rates of change of LEAFN in Figure 1.

Likewise, Figure 6 gives the rates of change of LEAFP with respect to each PPT index for both the estimated (dashed line) and the directly observed regression coefficients (solid line). Except for those rates in periods 3, 4, and 7, all the other rates were closely approximated by the rates from estimated coefficients. The changes in LEAFP in Figure 6 also showed the same pattern as the changes in LEAFN in Figure 2, because of the high correlation (r = 0.57) between them.

Additionally, these figures illustrate graphically that moisture stress and precipitation affect differentially LEAFP across the 40-day period before leaf sampling date. The PPT and DV indexes for the first period showed the previously indicated negative effects of high soil moisture on LEAFP. The responses of LEAFP to the DV indexes for periods 3 to 5 showed that soil moisture below the average decreased LEAFP, although the rate is lower in period 5. Moisture stress apparently was not a limiting factor in periods 2, 6, and 7, but the need for higher soil moisture close to silking was revealed by the positive response of LEAFP to DV8.

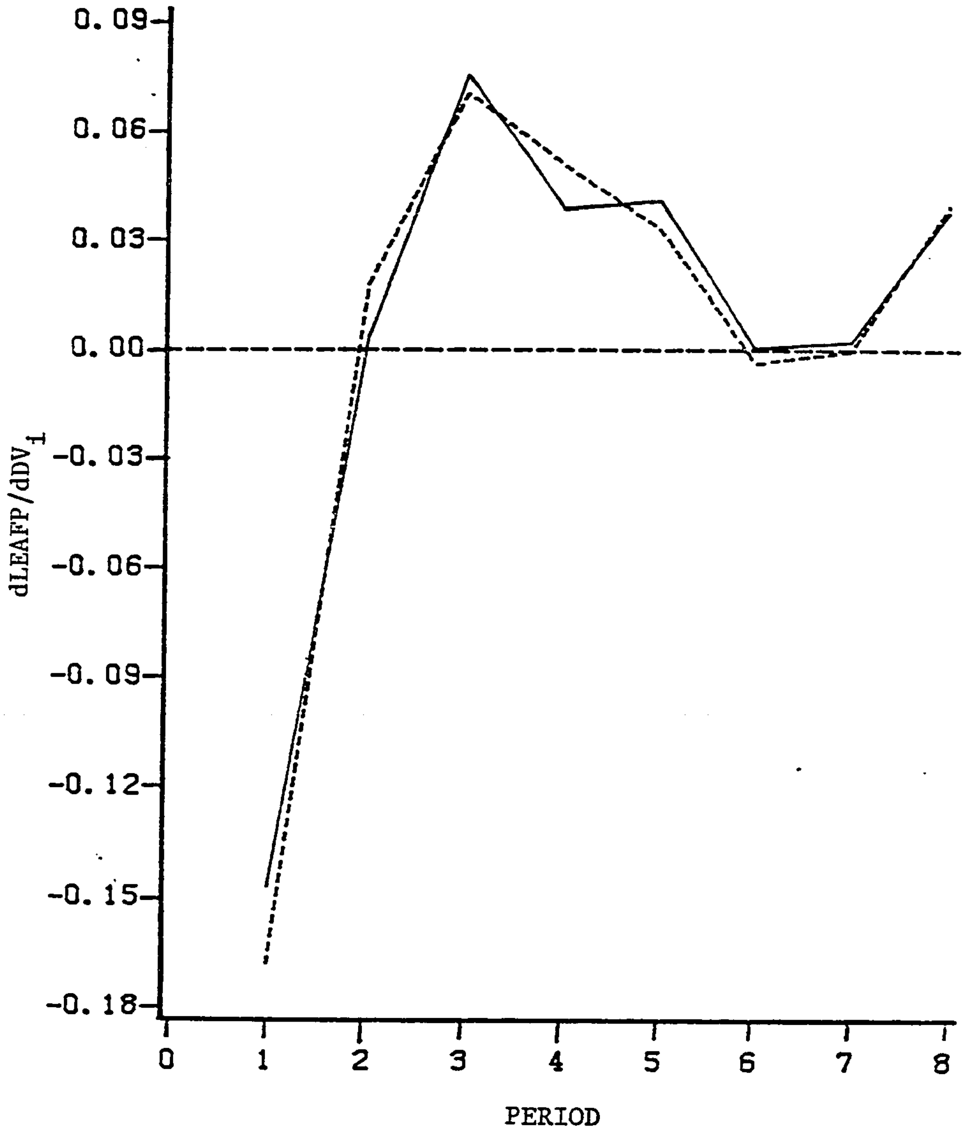

Figure 5. Rates of change of LEAFP with respect to each 5-day DV index as calculated from the directly observed regression coefficients (solid line) and from the estimated regression coefficients (dashed line)

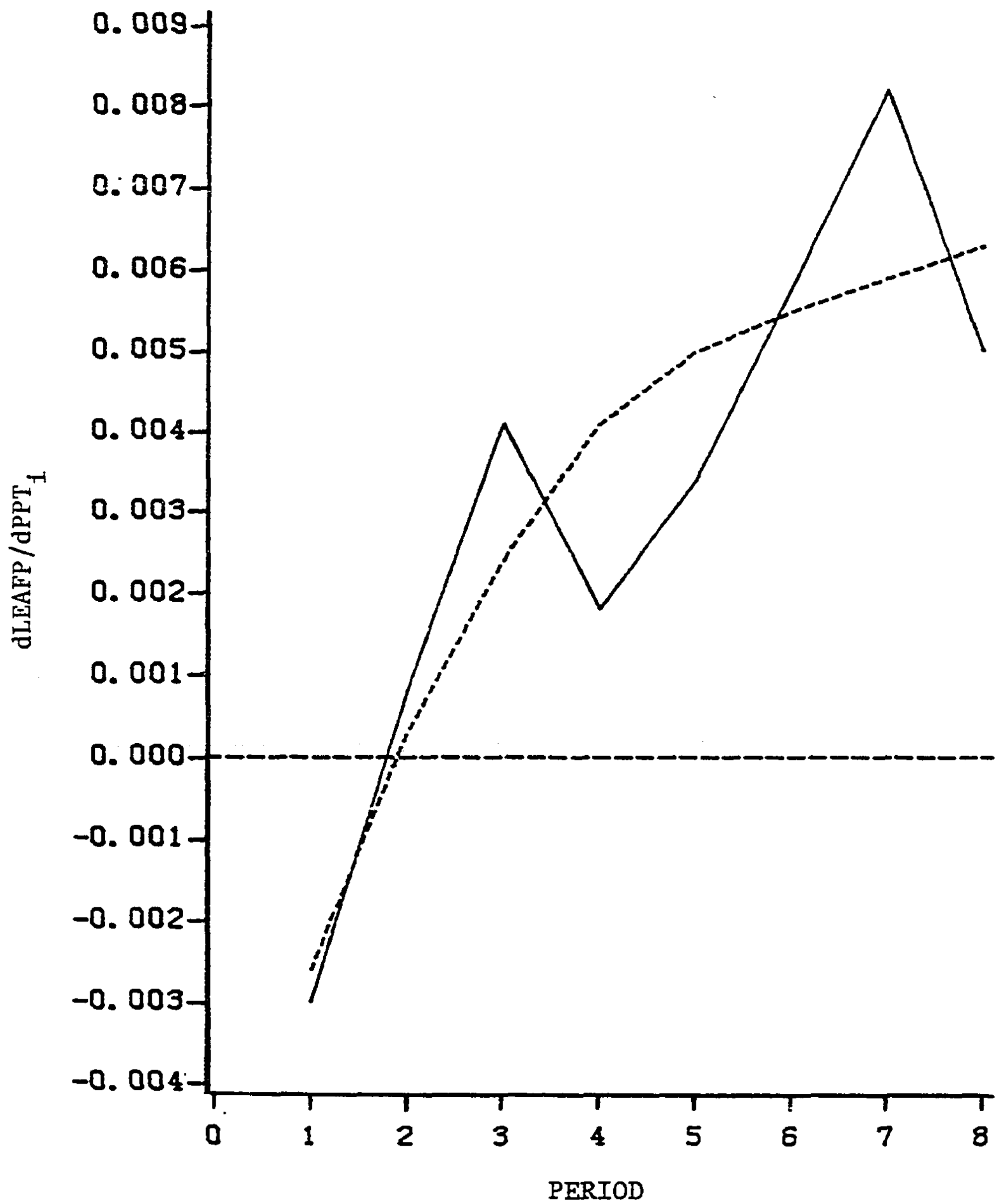

Figure 6. Rates of change of LEAFP with respect to each 5-day PPT index as calculated from the directly observed regression coefficients (solid line) and from the estimated regression coefficients (dashed line)

Likewise, the rate of change of LEAFP with respect to PPT1 showed the negative effect of high soil moisture early in the 40-day period, whereas the rates of change of LEAFP with respect to the PPT2 to PPT8 indexes showed that higher precipitation in those periods increased LEAFP. The responses increased from the first to the last period.

It was assumed that a third-order polynomial could represent the differential effects of the 5-day PPT and DV indexes on LEAFP across the 40-day period. Figure 5 suggested that the third-order polynomial represented accurately the relationships between LEAFP and the DV indexes, while Figure 6 indicated that a second-order polynomial would better represent the relationship between LEAFP and the 5-day PPT indexes.

Another way to check the proper order of the polynomial is to perform a stepwise, backward elimination of the nonsignificant summation variates representing the linear and squared functions of these indexes. This selection was executed on Model LEAFP-D5 to get Model LEAFP-D12. The regression statistics of the selected weather index variates are given in Table 38. The summation variates of a third-order polynomial representing both the linear and the squared functions of the DV indexes were significant, which confirmed that this polynomial represented accurately the differential effects of the DV indexes on LEAFP across the 40-day period.

Only the PPT summation variates for a first-order polynomial (PPTI and PPTL) were significant, while only the linear summation variate (PPTQL) representing the squared function of the PPT indexes was significant. These variates indicated that the responses of LEAFP to each

Table 38. Regression statistics of the summation variates of the weather indexes selected in reduced Models LEAFP-D12 and LEAFP-D13

Model LEAFP-D12[a]			Model LEAFP-D13[b]		
X_i	Variate	b_i	X_i	Variate	b_i
1	DVI	-1.100**	1	DVI	-1.025**
2	DVL	0.673**	2	DVL	0.652**
3	DVQ	-0.114**	3	DVQ	-0.111**
4	DVC	0.00566**	4	DVC	0.00558**
5	DVQI	2.496**	5	DVQI	2.314**
6	DVQL	-1.412**	6	DVQL	-1.364**
7	DVQQ	0.231**	7	DVQQ	0.228**
8	DVQC	-0.0114**	8	DVQC	-0.0114**
9	PPTI	-0.00165**	21	PPT15I	0.000423
10	PPTL	0.00134**	22	PPT15L	0.000821**
			23	PPT15Q	0.0000557**
14	PPTQL	-0.000143**			
			25	PPT15QI	-0.000229*
			26	PPT15QL	-0.000115**

[a]Intercept = 0.223**, R^2 = 0.450, and no. of variates = 47.

[b]Intercept = 0.210**, R^2 = 0.452, and no. of variates = 49.

PPT index increased linearly from one period to the other and that those responses were modified by a quadratic effect that decreased at a constant rate from one period to the other, as determined by the significant PPTQL summation variate.

A similar selection was performed on Model LEAFP-D11 containing the summation variates of the PPT15 indexes, and Model LEAFP-D13 was obtained whose regression statistics are given in Table 38. The summation variates of a third-order polynomial for the linear and squared variates of the DV indexes were retained, thus suggesting that the responses of LEAFP to each DV index varied from one period to another in a cubic fashion. For the PPT15 indexes, the summation variates of a second-order polynomial for the linear functions of these indexes were significant. Likewise, the summation variates of a first-order polynomial for the squared functions were retained. PPT15I was not significant but it was retained because the PPT15QI was significant. These variates showed that the linear responses of LEAFP with respect to each PPT15 index increased at an increasing rate from the first period to the last but they were modified by quadratic effects that decreased from the first period to the last at a constant rate.

Testing of the interactions

Model LEAFP-D13 was used as the base model for testing a number of interactions between weather indexes and soil or management variables. The variates of selected weather, soil, and management variables included in this model are listed in Table 39.

To test the interactions between the moisture stress and precipitation indexes and the soil and management variables, the summation variates for the linear effects of each index were multiplied by the linear variates of the selected soil or management variables. These interaction variates were added to the variates in base Model LEAFP-D13 until the 100 positions allowed by the HELARCTOS II program were filled. Thereafter, a stepwise, backward elimination of nonsignificant interaction variates was performed and the process was repeated by adding new interaction variates in the available positions.

Table 39. Base set of linear and squared variates included in the regression models to select interaction variates, Models LEAFP-E to LEAFP-J series

X_i	Variate	X_i	Variate	X_i	Variate
1	DVI	20	MANURE	37	EXMO
2	DVL	21	NBDCT		
3	DVQ	22	PBDCT	38	$SAMDIF^2$
4	DVC	23	PRES1	39	$PLDEN^2$
5	DVQI	24	PRES2	40	$CULT^2$
6	DVQL			41	$NBDCT^2$
7	DVQQ	25	PH1	42	$PBDCT^2$
8	DVQC	26	STN	43	$PRES1^2$
		27	STP1	44	$PRES2^2$
9	PPT15I			45	$PH1^2$
10	PPT15L	28	NCODE1	46	STN^2
11	PPT15Q	29	HYCROSS	47	$STP1^2$
12	PPT15QI			48	$NCODE1^2$
13	PPT15QL	30	THAHOR	49	$HYCROSS^2$
		31	PALEO	50	$THAHOR^2$
14	SAMDIF	32	SAND	51	$DCAL^2$
15	LEAFP[a]	33	COLLUV	52	$EXMO^2$
16	PLDEN	34	ALLUV		
17	CULT				
18	PLOW	35	DCAL		
19	PLDATE	36	STP2		

[a]LEAFP was the dependent variable regressed on the listed variates plus selected interaction variates.

In this manner, three series of regression models were computed which were the Models LEAFP-E, LEAFP-F, and LEAFP-G series. Table 40 lists the interactions tested in each series and the model selection steps are presented in Table 41.

The initial complete model in the Model LEAFP-E series included 47 interaction variates from which 22 were selected in Model LEAFP-E12 which had an R^2 that was 2.6% higher than that of the base model.

Table 40. Interaction variates included in the multiple regression Models LEAFP-E, LEAFP-F, and LEAFP-G series[a]

X_i	Model LEAFP-E	X_i	Model LEAFP-F	X_i	Model LEAFP-G
53[b]	DVI*PLDEN	53	DVI*PLDEN	53	DVI*THAHOR
54	DVL*	54	DVL*	54	DVL*
55	DVQ*	55	DVQ*	55	DVQ*
56	DVC*	56	DVC*	56	DVI*STP1
57	DVI*PBDCT	57	DVI*THAHOR	57	DVI*NBDCT
58	DVL*	58	DVL*	58	DVL*
59	DVQ*	59	DVQ*	59	DVQ*
60	DVC*	60	DVI*STN	60	DVC*
61	DVI*THAHOR	61	DVL*	61	DVI*SAMDIF
62	DVL*	62	DVQ*	62	DVL*
63	DVQ*	63	DVC*	63	DVQ*
64	DVC*	64	DVI*STP1	64	DVC*
65	DVI*STN	65	DVL*	86	PPT15I*STP1
66	DVL*	66	DVQ*	87	PPT15L*
67	DVQ*	67	DVI*NCODE1	95	PPT15I*THAHOR
68	DVC*	68	DVL*	96	PPT15I*PLDEN
69	DVI*STP1	69	PPT15I*PLDEN	97	PPT15L*
70	DVL*	70	PPT15L*	98	PPT15Q*
71	DVQ*	71	PPT15Q*	65[b]	DVI*PRES2
72	DVC*	72	PPT15I*STP1	66	DVL*
73	DVI*NCODE1	73	PPT15L*	67	DVQ*
74	DVL*	74	PPT15I*THAHOR	68	DVC*
75	DVQ*	75[b]	DVI*SAMDIF	69	DVI*PALEO
76	DVC*	76	DVL*	70	DVL*
77	PPT15I*PLDEN	77	DVQ*	71	DVQ*
78	PPT15L*	78	DVC*	72	DVC*
79	PPT15Q*	79	DVI*NBDCT	73	DVI*SAND
80	PPT15I*PBDCT	80	DVL*	74	DVL*
81	PPT15L*	81	DVQ*	75	DVQ*
82	PPT15Q*	82	DVC*	76	DVC*
83	PPT15I*NCODE1	83	DVI*PH1	77	PPT15I*SAMDIF
84	PPT15L*	84	DVL*	78	PPT15L*
85	PPT15Q*	85	DVQ*	79	PPT15Q*
86	PPT15I*STN	86	DVC*	80	PPT15I*NBDCT
87	PPT15L*				

[a]Variate 88 was a dummy variable.

[b]This variate and the variates below it were the new interaction variates added for testing.

Table 40. (Continued)

X_i	Model LEAFP-E	X_i	Model LEAFP-F	X_i	Model LEAFP-G
89	PPT15*STP1	99	EXMO*NBDCT	81	PPT15L*
90	PPT15L*	100	*PH1	82	PPT15Q*
91	PPT15Q*			83	PPT15I*PALEO
92	PPT15I*THAHOR			84	PPT15L*
93	PPT15L*			85	PPT15Q*
94	PPT15Q*			89	PPT15I*SAND
95	EXMO*PLDEN			90	PPT15L*
96	*PBDCT			91	PPT15Q*
97	*THAHOR			92	PPT15I*PRES2
98	*STN			93	PPT15L*
99	*STP1			94	PPT15Q*
100	*NCODE1			99	EXMO*PALEO
				100	*NCODE1

Because of the formatting error, some interactions that were originally included in the first model of the Model LEAFP-F series could not be properly tested; therefore, only 14 interaction variates were assessed in this series. After including new interation variates, some of the interaction variates already selected became nonsignificant. Selection was then performed on all interaction variates, and from the old ones and the new ones a total of 19 interaction variates were retained in Model LEAFP-F10.

In the Model LEAFP-G series, 28 new interaction variates were tested. After elimination of the nonsignificant interactions, Model LEAFP-G16 with an R^2 of 0.491 was obtained. This model contained 28 interaction variates of which 16 were interactions between the summation variates of the DV indexes and the THAHOR, STP1, NBDCT, SAMDIF, NCODE1, and SAND

Table 41. Model selection steps, Models LEAFP-E, LEAFP-F, and LEAFP-G series

Model no.	No. of X_i	Identification	R^2
LEAFP-E1	98	Complete model, base set of 51 variates (Table 39) plus 47 interaction variates	.482
E12	73	Reduced model, base set of 51 variates plus 22 selected interaction variates	.478
F1	87	Complete model, variates in Model LEAFP-E12 plus 14 interaction variates	.495
F10	70	Reduced model, base set of 51 variates plus 19 selected interaction variates	.481
G1	98	Complete model, variates in Model LEAFP-F10 plus 28 interaction variates	.496
G16	79	Reduced model, base set of 51 variates plus 28 selected interaction variates (from all previous series)	.491

variables. The remaining 12 were interactions between the summation variates of the PPT15 indexes and variates of the SAMDIF, NBDCT, STP1, SAND, and PLDEN variables. None of the evaluated interactions between the EXMO index and other variables was retained in Model LEAFP-G16. The inclusion of the selected interaction variates improved the R^2 in about 3.9% with respect to that of Model LEAFP-D13.

Next, three additional series of alternative regressions were computed to ascertain the effects on LEAFP of some interactions between variables of the soil and management group. Table 42 presents the interactions that were tested in the Models LEAFP-H, LEAFP-I, and LEAFP-J

Table 42. Interaction variates tested in multiple regression Models LEAFP-H to LEAFP-J series

X_i	Model LEAFP-H	X_i	Model LEAFP-I	X_i	Model LEAFP-J
81	STP1*NCODE1	89	STP1*PLOW	91	PBDCT*DCAL
82	*PBDCT	90	*PLDATE	92	*PH1
83	*THAHOR	91	*PALEO	93	*NCODE2
84	*PRES1	92	*SAND	94	*PLDEN
85	*MANURE	93	*ALLUV	95	*THAHOR
86	SAND*NBDCT			96	*PLDATE
87	*PBDCT	94	STP2*DCAL	97	*HYCROSS
88	Dummy	95	*MANURE		
89	PLDATE*PLDEN	96	*SAND	98	NCODE2*THAHOR
				99	*PRES1
90	NBDCT*STN	97	STN*MANURE	100	*PRES2
91	*NCODE1	98	NCODE1*SAMDIF		
92	NCODE1*STN	99	EXMO*PLDATE		
93	STP1*HYCROSS	100	*ALLUV		
94	*PRES2				
95	*SAMDIF				
96	STP2*PRES1				
97	*PRES2				
98	*PBDCT				
99	*NCODE1				
100	SAND*MANURE				

series, and the model selection steps followed in each series are given in Table 43.

Initial Model LEAFP-H1 included 19 interaction variates which increased the R^2 about 2.0% above that of Model LEAFP-G16. In this series, a total of 38 interaction variates were retained in the final model without change in the R^2.

Model LEAFP-I1 included 12 new interactions from which only 3 were selected. Two of the previously selected interactions became nonsignifi-

Table 43. Model selection steps, Models LEAFP-H, LEAFP-I, and LEAFP-J series

Model no.	No. of X_i	Identification	R^2
LEAFP-H1	98	Complete model, variates in base set plus 28 interactions selected in Model LEAFP-G16 plus 19 interaction variates	.511
H10	86	Reduced model, deleted $PBDCT^2$, $PRES1^2$, and $STP1^2$ plus 38 selected interactions from previous interaction models	.511
I1	98	Complete model, variates in Model LEAFP-H10 plus 12 interaction variates	.522
I7	88	Reduced model, 48 variates from base set plus 40 selected interactions from previous interaction models	.519
J1	98	Complete model, variates in Model LEAFP-I7 plus 10 interaction variates	.522
J19	75	Reduced model, 43 variates from base set plus 32 selected interactions from previous interaction models	.512

cant and were deleted along with the nonsignificant $EXMO^2$ variate. Final Model LEAFP-I7 attained an R^2 of 0.519.

Lastly, 10 interaction variates were added in Model LEAFP-J1 with only one being retained and another previously selected one being eliminated. In this series, those variates nonsignificant at the 5% level were deleted. Final Model LEAFP-J19 had an R^2 of 0.512 and a total of 75 variates (Table 43). The interactions between the soil and management variables increased the R^2 by 2.1% above that of Model LEAFP-G16, which included only interactions between the weather indexes and the soil and management variables. The R^2 of Model LEAFP-J19 was 0.142 or 14.2% larger than that of Model LEAFP-A20, the base model without weather indexes. Final Model LEAFP-J19 was next used to interpret the effects of selected weather, soil, and management variables on LEAFP.

In summary, in this final model, the EXMO index and the summation variates of the 5-day PPT15 and DV indexes explained 8.8% of the variability in LEAFP, their interactions with soil and management variables explained an additional 3.3%, and the interactions between variables of the soil and management group explained an additional 4.2% of the variability. Therefore, all of these effects accounted for a total of 16.3% of the variability in this leaf nutrient.

These results then suggested that the weather factors represented by the selected indexes exerted a direct, significant effect on LEAFP, probably by influencing, either positively or negatively, the P availability in the soil and its uptake and, to a lesser extent, through their interactions with some soil and management factors. Some of these effects on LEAFP may be indirect through the high correlation between LEAFN and LEAFP.

Interpretation of the final prediction Model LEAFP-J19

The regression statistics of the final interaction Model LEAFP-J19 are given in Table 44. This regression model included 21 linear and 9 squared variates of soil and management variables, 8 and 5 summation variates of the DV and PPT15 indexes, respectively, the linear variate of the EXMO index, 18 variates of interactions between weather and

Table 44. Regression statistics of the final interaction Model LEAFP-J19[a]

X_i	Variate[b]	b_i	X_i	Variate	b_i
1	DVI (2.18)	-1.282**	42	PRES2^2	-0.00000495*
2	DVL (11.4)	0.827**	43	PH1^2	-0.0000924**
3	DVQ (70.5)	-0.144**	44	STN^2	-0.0000121**
4	DVC (473.3)	0.00745**	45	NCODE1^2	0.0000481**
5	DVQI	2.251**	47	THAHOR^2	-0.00000937**
6	DVQL	-1.285**	48	DCAL^2	-0.00000150**
7	DVQQ	0.211**	49	DVI*THAHOR	0.00659**
8	DVQC	-0.0104*	50	DVL*	-0.00283**
9	PPT15I (11.2)	-0.00411**	51	DVQ*	0.000262**
10	PPT15L (-2.36)	0.000652**	52	DVI*STP1	-0.000401**
11	PPT15Q (210.8)	0.000198**	53	DVI*NBDCT	0.00280**
12	PPT15QI	-0.000327**	54	DVL*	-0.00275**
13	PPT15QL	-0.000103**	55	DVQ*	0.000654**
14	SAMDIF (0.8)	0.0000184	56	DVC*	-0.0000444**
16	PLDEN (380)	-0.000304**	57	DVI*SAMDIF	-0.0396*
18	PLOW (0.7)	-0.00351*	58	DVL*	0.0176*
19	PLDATE (23)	0.000891**	59	DVQ*	-0.00165*
20	MANURE (5)	0.000625**	65	PPT15L*SAMDIF	-0.0000943**
21	NBDCT (68)	0.000567**	67	PPT15I*NBDCT	-0.00000891*
22	PBDCT (9)	0.000270*	68	PPT15L*STP1	0.00000432**
23	PRES1 (13)	0.000368**	69	PPT15I*SAND	-0.00348**
24	PRES2 (13)	0.000341**	70	PPT15Q*	0.000129**
25	PH1 (15)	0.00414**	71	PPT15I*PLDEN	0.0000150**
26	STN (63)	0.00196**	72	PPT15Q*	-0.000000394**
27	STP1 (33)	0.00223**	74	STP1*PBDCT	-0.00000651**
28	NCODE1 (23)	-0.00366**	76	*PRES1	-0.00000398**
29	HYCROSS (2)	-0.000898	77	*MANURE	-0.00000910**
30	THAHOR (34)	0.0000846	83	*HYCROSS	-0.0000665**
31	PALEO (0.03)	-0.0336**	85	*PLDATE	-0.0000134**
32	SAND (0.1)	0.0263**	86	*PALEO	0.000733*
34	ALLUV (0.1)	0.0128**	87	*ALLUV	-0.000248**
35	DCAL (30)	-0.0000534	84	STP2*PRES1	-0.00000595**
36	STP2 (18)	0.000264**	89	*DCAL	0.0000111**
37	EXMO (1)	-0.00176**	78	SAND*NBDCT	-0.000155**
			79	*PBDCT	0.000995**
38	SAMDIF^2	-0.000514**	80	NBDCT*STN	-0.00000327**
39	PLDEN^2	0.000000182*	82	NCODE1*STN	0.0000119*
41	NBDCT^2	-0.000000497**	91	PBDCT*DCAL	0.00000346**

[a]Intercept = 0.180 and R^2 = 0.512.

[b]Rounded means of the variables are given in the parentheses.

soil and management variables, and 14 variates of interactions between variables of the soil and management group. The effects on LEAFP of the variables included in the final model will be next discussed.

Weather indexes The EXMO index, which represents the excess moisture conditions during the 46-day period starting 3 days after planting, exerted a negative, linear effect on LEAFP (dLEAFP/dEXMO = -0.00176). Maximum reduction in LEAFP at EXMO = 15 was 0.025%. The EXMO effect was not affected by any interaction with soil or management variables.

The first derivatives of LEAFP with respect to each DV index were calculated by following the procedure similar to that in the LEAFN section and are listed in Table 45. They show that the rates of change of LEAFP with respect to the 5-day DV indexes varied across the 40-day period before leaf sampling date. The linear components of the 5-day DV indexes (shown in the C column in Table 45) varied in a cubic manner from a negative value for DV1, to an inflexion point between DV2 and DV3, to a maximum value for DV4, and then to a negative one for DV8, as determined by the third-order function of the DV_i linear components shown in Table 44. The total rates of change of LEAFN were also influenced by the quadratic components of the DV_i indexes which also varied in a cubic manner as shown in the DV_i column of Table 45.

The linear rates of change of LEAFP (in the C column in Table 45) were also modified by the levels of the interacting variables of THAHOR, STP1, NBDCT, and SAMDIF. At fixed levels of the interacting variables, the constant in the partial derivative was increased or decreased

Table 45. First partial derivatives of LEAFP on each 5-day DV index, calculated from the regression coefficients in Model LEAFP-J19

$dLEAFP/dDV_i$ for following DV_i[a]	Coefficients of the quadratic function of DV_i and its interactions with the following variables in the partial derivative					
	C	DV_i	THAHOR	STP1	NBDCT	SAMDIF
DV1	-0.592	2.334	0.00402	-0.000401	0.000669	-0.0236
DV2	-0.146	0.885	0.00198	-0.000401	-0.000445	-0.0110
DV3	0.101	0.0306	0.000469	-0.000401	-0.000774	-0.00166
DV4	0.193	-0.355	-0.000523	-0.000401	-0.000554	0.00439
DV5	0.175	-0.396	-0.000991	-0.000401	-0.000121	0.00715
DV6	0.0912	-0.219	-0.000935	-0.000401	0.000288	0.00663
DV7	-0.0131	0.0521	-0.000355	-0.000401	0.000406	0.00280
DV8	-0.0934	0.291	0.000749	-0.000401	-0.000033	-0.00431

[a]First partial derivatives of LEAFP with respect to each 5-day DV index where $i = 1,2,\ldots 8$.

depending on the sign of the interaction with the DV_i variate. As previously explained, these interactions increased or decreased the initial slope at the intercept and the DV_i values associated with maximum or minimum LEAFP. The coefficients for the interactions with THAHOR and SAMDIF varied quadratically across the eight 5-day periods, those with NBDCT varied in a cubic manner, and those with STP1 were constant in all periods.

The mean rates of change of LEAFP with respect to each DV index were calculated by substituting into the partial derivatives the mean values of the respective DV indexes and of all the interacting variables. Figure 7 presents graphically the distribution of the rates of change across the eight 5-day periods before leaf sampling date. The rates of change of LEAFP to the DV indexes changed from negative to DV1, to a maximum and positive rate to DV3, then to a minimum to DV6, and, again, increased to a more positive rate of change to DV8. This cubic distribution of the rates of change of LEAFP with respect to the 5-day DV indexes was similar to that in Figure 5 and to the $dLEAFN/dDV_i$ distribution in Figure 3. Their agronomic significance is also similar to that discussed previously.

To illustrate the interactions between the 5-day DV indexes and the THAHOR (thickness of A horizon) variable on LEAFP, the first partial derivatives were simplified for values of THAHOR of 10 and 30 cm, with the other interacting variables set at STP1 = 40, NBDCT = 125, and SAMDIF = 1. The reduced derivatives for both levels of THAHOR and the values of each DV index associated with maximum or minimum LEAFP are given in Table 46.

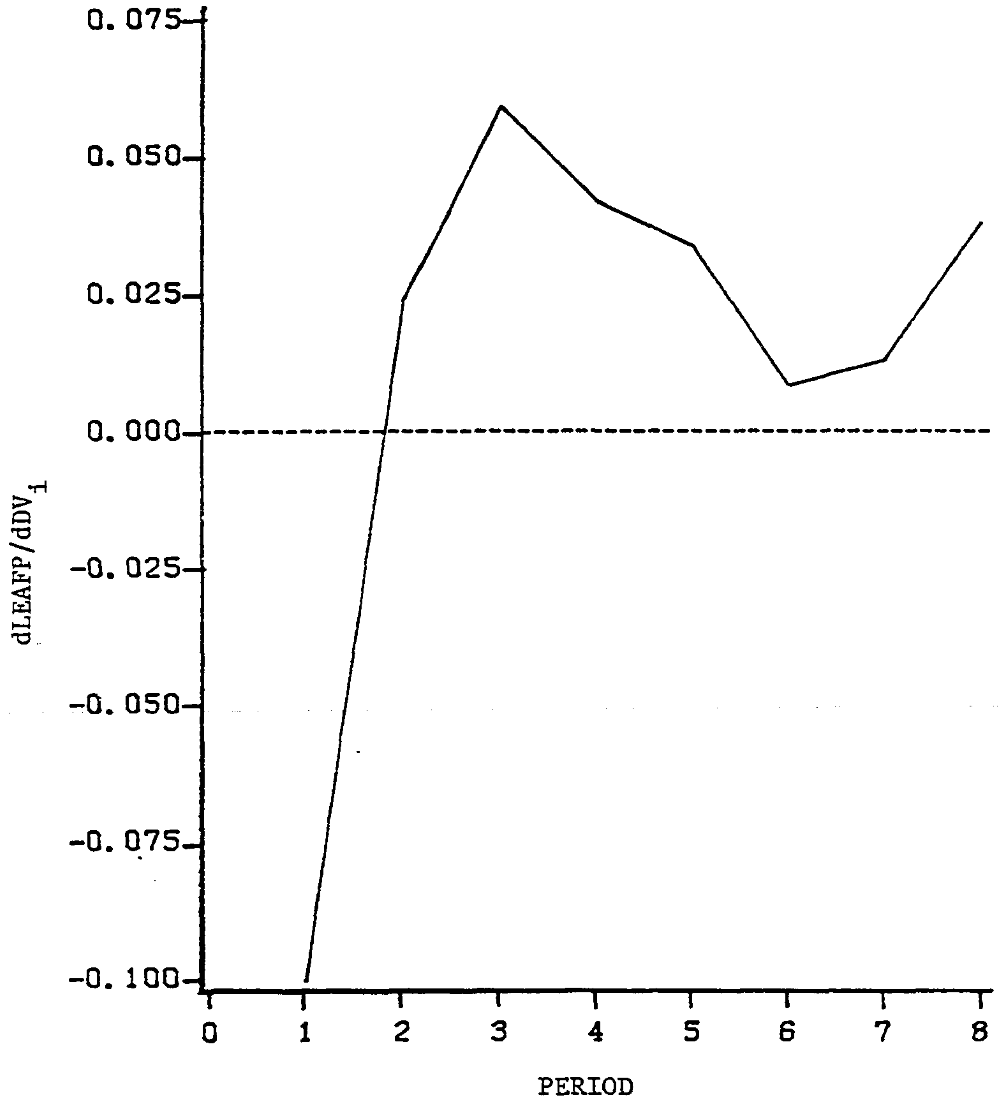

Figure 7. Rates of change of LEAFP with respect to each 5-day DV index at average values of all variables in the first partial derivatives (Table 45)

Table 46. Simplified first partial derivatives of LEAFP on each 5-day DV index at two levels of THAHOR, final Model LEAFP-J19

THAHOR (cm)	Simplified $dLEAFP/dDV_i$ =	Quadratic effect[b]	DV_i[a] Mean	DV_i[a] Range
10	-0.508 + 2.334 DV1	MIN at 0.22	0.15	0.01-0.2
	-0.206 + 0.885 DV2	MIN at 0.23	0.18	0.04-0.3
	-0.005 + 0.031 DV3	MIN at 0.16	0.25	0.08-0.4
	0.107 - 0.354 DV4	MAX at 0.30	0.24	0.07-0.4
	0.141 - 0.396 DV5	MAX at 0.35	0.23	0.05-0.4
	0.108 - 0.219 DV6	MAX at 0.50	0.29	0.04-0.5
	0.021 + 0.052 DV7	MIN at -0.40	0.40	0.05-0.6
	-0.110 + 0.291 DV8	MIN at 0.38	0.43	0.06-0.7
30	-0.427 + 2.334 DV1	MIN at 0.18	-	-
	0.166 + 0.885 DV2	MIN at -0.19	-	-
	0.004 + 0.031 DV3	MIN at -0.14	-	-
	0.096 - 0.354 DV4	MAX at 0.27	-	-
	0.121 - 0.396 DV5	MAX at 0.30	-	-
	0.090 - 0.219 DV6	MAX at 0.41	-	-
	0.014 + 0.052 DV7	MIN at -0.26	-	-
	-0.095 + 0.291 DV8	MIN at 0.33	-	-

[a]The DV_i (DV1 to DV8) means and ranges are listed in order; those associated with THAHOR = 30 are the same as listed for THAHOR = 10.

[b]Values of the DV indexes associated with maximum (MAX) or minimum (MIN) LEAFP.

First, the regression coefficients of the THAHOR*DV_i interactions (Table 45) showed that greater THAHOR (thickness of A horizon) increased the curvilinear responses of LEAFP to the DV indexes in periods 1 to 3 and 8 and decreased them in periods 4 to 7.

As Table 46 shows, the effects of moisture stress on LEAFP, as affected by the levels of THAHOR, varied across the 40-day period before leaf sampling. The initial slopes, the magnitudes of the positive or negative responses (not shown), and the DV_i levels associated with maximum or minimum LEAFP were affected by the interactions with THAHOR.

In the first three periods, greater THAHOR increased the LEAFP response to increasing DV, i.e., at less THAHOR, a higher DV was required to increase LEAFP. These effects indicate the advantage of having the plow layer moist in soils with thinner A horizons in the first part of the 40 days prior to leaf sampling in order to maintain higher availability of N and P. The initial negative effect of increasing DV on LEAFP at severe moisture stress on the thinner A horizon cannot be explained.

On the other hand, in periods 4, 5, and 6, increasing DV had similar effects on LEAFP except that higher DV was required to get the maximum LEAFP at the low level than at the high level of THAHOR. This indicated that more soil moisture (or less soil moisture stress) was needed to maximize P uptake in soils with thinner A horizons. The negative effect of high soil moisture conditions at DV levels above to considerably above their means probably was due to losses of available N that affected LEAFP indirectly through the parallel relationship between LEAFN and LEAFP ($r = 0.57$).

In period 7, increasing DV (less moisture stress) increased LEAFP for all THAHOR levels. In period 8, the effects of DV on LEAFP were reversed, with LEAFP decreasing from severe to moderate moisture stress to a minimum and then increasing with increased moisture. The THAHOR had a slight effect on the LEAFP response. The reason for the different

LEAFP responses to DV in period 8 is not known.

To illustrate the interaction between the 5-day DV indexes and the STP1 (soil test P in the plow layer) variable, the first partial derivatives (Table 45) were simplified for levels of STP1 of 20 and 60 pp2m. The other interacting variables were set at THAHOR = 25, NBDCT = 125, and SAMDIF = 1. The simplified derivatives and the values of the DV indexes associated with maximum or minimum LEAFP are listed in Table 47.

First, the coefficients for the interactions between the DV indexes and STP1 were the same and negative for all periods (Table 45). These indicated that higher STP1 levels decreased the curvilinear responses of LEAFP to each DV index or, conversely, that lower STP1 levels increased the LEAFP response to increasing DV_i (less moisture stress).

As shown in Table 47, the effects on LEAFP of DV1 and DV2 were similar at both levels of STP1. In these periods, increased DV levels decreased LEAFP at a decreasing rate reaching a minimum LEAFP at the upper limit of the DV1 range and above the mean DV2. These effects suggested that, early in the 40-day period prior to leaf sampling, increased soil moisture decreased LEAFP as it had decreased the highly correlated LEAFN. In the third (transition) period, DV3 increased LEAFP over its entire range at low STP1 but had the same effect as in the earlier periods at the high STP1 level.

In periods 4 to 6, the effects of the respective DV indexes on LEAFP were similar at both STP1 levels (Table 47). Increased DV increased LEAFP at a decreasing rate in all periods over most of the DV relevant ranges. Maximum LEAFP was reached at slightly higher DV levels at the

Table 47. Simplified first partial derivatives of LEAFP on each 5-day DV index at two levels of STP1, final Model LEAFP-J19

STP1 (pp2m P)	Simplified $dLEAFP/dDV_i$ =	Quadratic effect[a]
20	-0.439 + 2.344 DV1	MIN at 0.19
	-0.168 + 0.885 DV2	MIN at 0.19
	0.010 + 0.031 DV3	MIN at -0.33
	0.107 - 0.354 DV4	MAX at 0.30
	0.134 - 0.396 DV5	MAX at 0.34
	0.102 - 0.219 DV6	MAX at 0.47
	0.023 + 0.052 DV7	MIN at -0.45
	-0.091 + 0.291 DV8	MIN at 0.31
60	-0.455 + 2.334 DV1	MIN at 0.19
	-0.184 + 0.885 DV2	MIN at 0.21
	-0.006 + 0.031 DV3	MIN at 0.20
	0.091 - 0.354 DV4	MAX at 0.26
	0.118 - 0.396 DV5	MAX at 0.30
	0.086 - 0.219 DV6	MAX at 0.39
	0.007 + 0.052 DV7	MIN at -0.14
	-0.107 + 0.291 DV8	MIN at 0.37

[a]Values of the DV_i indexes associated with maximum (MAX) or minimum (MIN) LEAFP; the DV_i (DV1 to DV8) means and ranges are given in Table 46.

low than at the high STP1 level. These responses suggested that increased soil moisture in these periods favored P uptake, particularly if soil P in the plow layer was low. In period 7, increasing DV throughout its range increased LEAFP and somewhat more at low than at high STP1. The DV effect on LEAFP in period 8 was different and cannot be explained.

The DV_i*NBDCT interactions (Table 45) affected the rates of change of LEAFP to the DV indexes in a similar manner as they affected LEAFN, except in period 8 (Table 24). That is, the adverse effects of either high soil moisture conditions or moisture stress on LEAFP were offset by higher levels of applied N, thus suggesting that applied N also affected P uptake, as has been frequently reported in the literature. The DV_i*SAMDIF interactions also had similar effects on LEAFP and LEAFN. These will be discussed later.

The effects on LEAFP of the fifteen 5-day precipitation indexes were also investigated by applying the same procedure followed for the DV indexes. Table 48 presents the first partial derivatives of LEAFP with respect to each PPT15 index. The linear components of the 5-day PPT15 indexes (shown in the C column in Table 48) varied in a quadratic manner over the 15 periods, decreasing to a minimum in period 6 and then increasing at an increasing rate as determined by the second-order function of the linear components of these indexes (Table 44). The total rates of change were also modified by the quadratic components of the PPT15 indexes which decreased linearly from a positive value for PPT15-1 to a negative one for PPT15-15.

The linear rates of change of LEAFP with respect to each PPT15 index were increased or decreased by the levels of the SAMDIF, STP1, SAND, PLDEN, and NBDCT, depending on the signs of their interactions with the respective PPT15 index. The coefficients for the PPT15-i interactions with NBDCT were constant, those with SAMDIF and STP1 varied linearly, and those with SAND and PLDEN varied quadratically, as determined by their interactions with the respective summation variates of the PPT15 indexes as shown in Table 44.

The mean values of each PPT15 index were substituted into the partial derivatives (Table 48), maintaining all other variables at their

Table 48. First partial derivatives of LEAFP on each 5-day PPT15 index, calculated from the estimated regression coefficients in Model LEAFP-J19

dLEAFP/dPPT15-i[a] for following PPT15-i	Coefficients of the quadratic function of PPT15-i and of the interactions between PPT15 indexes and the following variables in the partial derivatives[b]					
	C	PPT15-i	SAMDIF	STP1	SAND	PLDEN
PPT15-1	0.00102	0.000788	0.000660	-0.0000301	0.00284	-0.0000046
PPT15-2	-0.000897	0.000582	0.000566	-0.0000258	0.00116	0.0000006
PPT15-3	-0.00242	0.000376	0.000471	-0.0000215	-0.00026	0.0000050
PPT15-4	-0.00355	0.000170	0.000377	-0.0000172	-0.00142	0.0000086
PPT15-5	-0.00429	-0.000036	0.000283	-0.0000129	-0.00232	0.0000114
PPT15-6	-0.00462	-0.000242	0.000189	-0.0000086	-0.00297	0.0000134
PPT15-7	-0.00457	-0.000448	0.000094	-0.0000043	-0.00336	0.0000146
PPT15-8	-0.00411	-0.000654	0.000000	0.0000000	-0.00348	0.0000150
PPT15-9	-0.00326	-0.000860	-0.000094	0.0000043	-0.00336	0.0000146
PPT15-10	-0.00202	-0.00107	-0.000189	0.0000086	-0.00297	0.0000134
PPT15-11	-0.000375	-0.00127	-0.000283	0.0000129	-0.00232	0.0000114
PPT15-12	0.00166	-0.00148	-0.000377	0.0000172	-0.00142	0.0000086
PPT15-13	0.00410	-0.00168	-0.000471	0.0000215	-0.00026	0.0000050
PPT15-14	0.00693	-0.00189	-0.000566	0.0000258	0.00116	0.0000006
PPT15-15	0.0101	-0.00210	-0.000660	0.0000301	0.00284	-0.0000046

[a]First partial derivatives of LEAFP with respect to each 5-day PPT15 index, where i=1,2,...15.

[b]Other coefficient in the partial derivative for all 15 periods is: -0.0000089 NBDCT.

mean values, and the rates of change of LEAFP with respect to each PPT15 index were obtained. These rates are plotted in Figure 8.

The curve confirms graphically the quadratic manner in which these rates changed across the 15 periods, as indicated by the summation variates (Table 44). That is, the rates increased from a negative value at an increasing rate throughout the 15 periods.

This figure shows that, in periods 1 to 6, average levels of rainfall, other factors constant, had negative responses on LEAFP. These effects agreed with the EXMO effects that corresponded to about the same stage of growth. From period 7 on, average levels of rainfall in each period were conducive to increasingly positive responses of LEAFP to rainfall, which indicated that higher LEAFP responses to soil moisture occurred as the time of silking or sampling approached.

As already stated, only five interactions between the PPT15 indexes and soil and management variables were detected which affected the responses of LEAFP to the precipitation indexes. In this part, only the interactions with STP1 and PLDEN variables will be discussed.

To illustrate the effects on LEAFP of the interactions between the 5-day PPT15 indexes and the STP1 variable, the first derivatives (Table 48) were simplified for soil test P levels of 20 and 60 pp2m. Other interacting variables were kept constant at the following levels: NBDCT = 125, PLDEN = 375, SAMDIF = 1, and SAND = 0. The simplified derivatives and the levels of the PPT15 indexes associated with maximum or minimum LEAFP are shown in Table 49.

First, inspection of the coefficients corresponding to the inter-

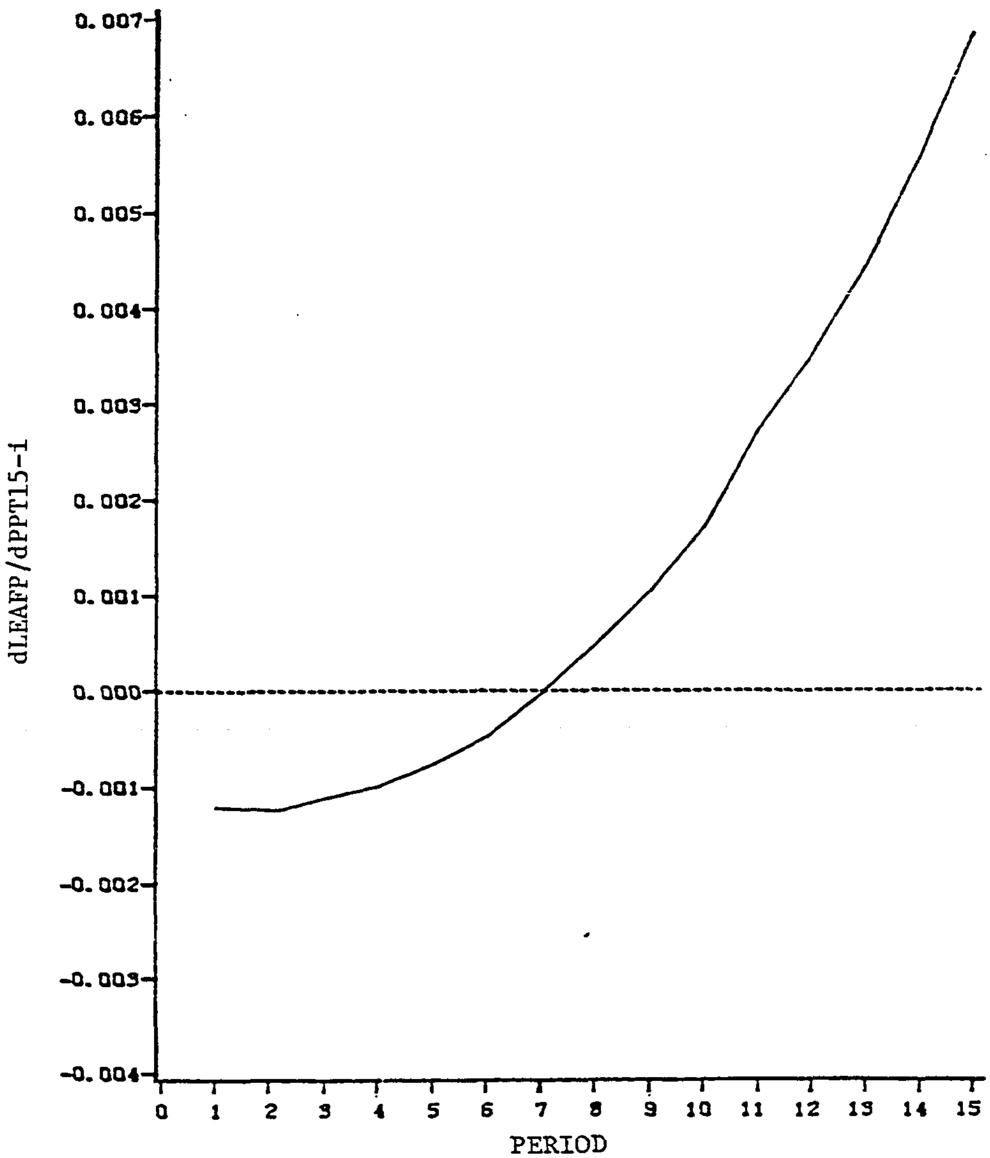

Figure 8. Rates of change of LEAFP with respect to each 5-day PPT15 index at average values of all variables in the first partial derivatives (Table 48)

Table 49. Simplified first partial derivatives of LEAFP on each 5-day PPT15 index at two levels of STP1, final Model LEAFP-J19

STP1 (pp2m P)	Simplified dLEAFP/dPPT15-i =	Quadratic effect[a]	PPT15-i (in.)	
			Mean	Range
20	-0.00175 + 0.000788 PPT15-1	MIN at 2.2	0.77	0-8.2
	-0.00173 + 0.000582 PPT15-2	MIN at 3.0	0.90	0-6.8
	-0.00162 + 0.000376 PPT15-3	MIN at 4.3	0.81	0-7.5
	-0.00141 + 0.000170 PPT15-4	MIN at 8.3	0.77	0-10.7
	-0.00110 - 0.000036 PPT15-5	MAX at -30.5	0.81	0-8.1
	-0.00069 - 0.000242 PPT15-6	MAX at -2.9	0.62	0-6.2
	-0.00020 - 0.000448 PPT15-7	MAX at -0.4	0.65	0-7.5
	0.00040 - 0.000654 PPT15-8	MAX at 0.6	0.77	0-8.3
	0.00109 - 0.000860 PPT15-9	MAX at 1.3	0.81	0-8.6
	0.00188 - 0.00107 PPT15-10	MAX at 1.8	0.83	0-6.2
	0.00276 - 0.00127 PPT15-11	MAX at 2.2	0.63	0-8.2
	0.00374 - 0.00148 PPT15-12	MAX at 2.5	0.71	0-7.9
	0.00482 - 0.00168 PPT15-13	MAX at 2.9	0.74	0-6.9
	0.00599 - 0.00189 PPT15-14	MAX at 3.2	0.71	0-7.7
	0.00726 - 0.00210 PPT15-15	MAX at 3.5	0.66	0-7.5
60	-0.00296 + 0.000788 PPT15-1	MIN at 3.7	-	-
	-0.00277 + 0.000582 PPT15-2	MIN at 4.7	-	-
	-0.00248 + 0.000376 PPT15-3	MIN at 6.6	-	-
	-0.00209 + 0.000170 PPT15-4	MIN at 12.3	-	-
	-0.00161 - 0.000036 PPT15-5	MAX at -44.8	-	-
	-0.00104 - 0.000242 PPT15-6	MAX at -4.3	-	-
	-0.00037 - 0.000448 PPT15-7	MAX at -0.8	-	-
	0.00040 - 0.000654 PPT15-8	MAX at 0.6	-	-
	0.00126 - 0.000860 PPT15-9	MAX at 1.5	-	-
	0.00222 - 0.00107 PPT15-10	MAX at 2.1	-	-
	0.00328 - 0.00127 PPT15-11	MAX at 2.6	-	-
	0.00443 - 0.00148 PPT15-12	MAX at 3.0	-	-
	0.00568 - 0.00168 PPT15-13	MAX at 3.4	-	-
	0.00702 - 0.00189 PPT15-14	MAX at 3.7	-	-
	0.00846 - 0.00210 PPT15-15	MAX at 4.0	-	-

[a]Values of the PPT15-i indexes associated with maximum (MAX) or minimum (MIN) LEAFP.

actions between the PPT15 indexes and STP1 (Table 48) showed that the initial responses of LEAFP to the PPT15 indexes at the intercept became more negative with increased levels of STP1 in periods 1 to 7, while the reverse occurred in periods 9 to 15.

As shown in Table 49, increasing amounts of rainfall in periods 1 to 4 decreased LEAFP at a decreasing rate to minimum values associated with PPT15 values much above their means. The minimum LEAFP occurred at lower PPT15 values at the low than at the high level of STP1, although these PPT15 values were in their upper relevant ranges. Increasing PPT15 in these first four periods decreased LEAFP over most of their relevant ranges and at a somewhat faster rate at a high than at a low STP1 level. The higher rainfall reduced P uptake and LEAFP; part of this probably was indirect through the rainfall effect on LEAFN.

In periods 5 to 7, calculated maximum levels of LEAFP were at negative PPT15 values; this simply means that over the entire relevant PPT15 ranges, increasing rainfall decreased LEAFP at an increasing rate. Thus, in these periods, as in the previous four periods, increasing rainfall decreased LEAFP and somewhat more as STP1 rates increased.

In periods 8 and 9, the responses of LEAFP to the respective PPT15 indexes were similar at both levels of STP1. Increased precipitation initially increased LEAFP which maximized at PPT15 levels slightly below to above their means and then it decreased LEAFP. These responses showed that the effects of precipitation on LEAFP were changing gradually from negative to positive through the first 9 periods, probably because soil moisture was gradually decreasing due to increased water demand by the corn.

In periods 10 to 15, increasing precipitation increased LEAFP at a decreasing rate which reached a maximum at higher levels of precipitation over time (Table 49). The levels of the PPT15 indexes associated with maximum LEAFP were somewhat higher at the high than at the low STP1 levels. These responses suggested that, from about 30 days before to the leaf sampling date, increased rainfall increased the levels of LEAFP, particularly if soil P was high, thus revealing the need for adequate soil moisture during this critical growth period. However, LEAFP also was decreased by large amounts of rainfall, probably through an indirect effect on available N or because high soil moisture in the plow layer reduced the P uptake, particularly if soil P was low.

For the effects of the interactions between the PPT15 indexes and PLDEN, the first derivatives (Table 48) were simplified for PLDEN levels of 300 and 600 plants/0.01 ha (30,000 and 60,000 plants/ha). The other interacting variables were kept constant at: STP1 = 40, NBDCT = 125, SAMDIF = 1, and SAND = 0. The simplified derivatives and levels of the PPT15 indexes associated with maximum and minimum LEAFP are shown in Table 50.

First, the regression coefficients for the interactions between the PPT15 indexes and PLDEN (Table 48) showed that, in periods 2 to 14, higher levels of PLDEN increased the curvilinear responses of LEAFP to the respective PPT15 indexes, while in periods 1 and 15, the responses were decreased.

As shown in Table 50, at the low level of PLDEN, increased precipita-

Table 50. Simplified first partial derivatives of LEAFP on each 5-day PPT15 index at two levels of PLDEN, final Model LEAFP-J19

PLDEN (plants/ha)	Simplified dLEAFP/dPPT15-i =	Quadratic effect[a]
30,000	-0.00201 + 0.000788 PPT15-1	MIN at 2.6
	-0.00229 + 0.000582 PPT15-2	MIN at 3.9
	-0.00242 + 0.000376 PPT15-3	MIN at 6.4
	-0.00240 + 0.000170 PPT15-4	MIN at 14.1
	-0.00221 - 0.000036 PPT15-5	MAX at -61.0
	-0.00187 - 0.000242 PPT15-6	MAX at -7.7
	-0.00138 - 0.000448 PPT15-7	MAX at -3.1
	-0.000725 - 0.000654 PPT15-8	MAX at -1.1
	0.000083 - 0.000860 PPT15-9	MAX at 0.1
	0.00104 - 0.00107 PPT15-10	MAX at 1.0
	0.00216 - 0.00127 PPT15-11	MAX at 1.7
	0.00344 - 0.00148 PPT15-12	MAX at 2.3
	0.00487 - 0.00168 PPT15-13	MAX at 2.9
	0.00646 - 0.00189 PPT15-14	MAX at 3.4
	0.00820 - 0.00210 PPT15-15	MAX at 3.9
60,000	-0.00339 + 0.000788 PPT15-1	MIN at 4.3
	-0.00211 + 0.000582 PPT15-2	MIN at 3.6
	-0.00092 + 0.000376 PPT15-3	MIN at 2.5
	0.00018 + 0.000170 PPT15-4	MIN at -1.1
	0.00121 - 0.000036 PPT15-5	MAX at 33.5
	0.00215 - 0.000242 PPT15-6	MAX at 8.9
	0.00300 - 0.000448 PPT15-7	MAX at 6.7
	0.00377 - 0.000654 PPT15-8	MAX at 5.8
	0.00446 - 0.000860 PPT15-9	MAX at 5.2
	0.00506 - 0.00107 PPT15-10	MAX at 4.8
	0.00558 - 0.00127 PPT15-11	MAX at 4.4
	0.00602 - 0.00148 PPT15-12	MAX at 4.1
	0.00637 - 0.00168 PPT15-13	MAX at 3.8
	0.00664 - 0.00189 PPT15-14	MAX at 3.5
	0.00682 - 0.00210 PPT15-15	MAX at 3.3

[a]Values of the PPT15-i indexes associated with maximum (MAX) or minimum (MIN) LEAFP; the PPT15-i (PPT15-1 to PPT15-15) means and ranges are given in Table 49.

tion decreased LEAFP over most or all of the relevant ranges of PPT15 through period 9. In period 10, LEAFP increased with precipitation to a maximum at slightly above the mean PPT15-10 level. From periods 11 to 15, the PPT15 indexes had positive effects on LEAFP and up to increasingly higher PPT15 levels. In these last periods, high rainfall still could have a negative effect on LEAFP, probably because of its effects on N losses and decreased LEAFN.

The effects of the PPT15 indexes on LEAFP at the high PLDEN level, however, were considerably different from those described at the low PLDEN level. In the three earliest periods, increased PPT15 decreased LEAFP over most of their relevant ranges. However, from periods 4 to 15, increased PPT15 increased LEAFP levels over all to most of the PPT15 ranges.

These results show that higher plant densities decreased the negative effects of high precipitation levels on LEAFP from periods 3 to 13, probably because of increased transpiration (moisture demands) from the higher plant densities and subsequent soil moisture depletion. The greater positive effects of increased precipitation on LEAFP in the 50-60 days before leaf sampling at the higher plant density levels indicate the importance of maintaining adequate moisture in the soil surface or plow layer for maximum uptake of soil and fertilizer P.

The interactions between the PPT15 indexes and NBDCT, which had constant coefficients over all periods (Table 48), showed that increased levels of NBDCT decreased the curvilinear responses of LEAFP to all the PPT15 indexes, hence demonstrating once more the effect that N applications exert on P uptake and leaf concentration. On the other hand, the interactions between the PPT15 indexes and the SAND variable (Table 48) showed that, in most periods, more negative or less positive responses of LEAFP to the PPT15 indexes occurred in soils with sandy parent materials. This effect may be related to more N leaching, particularly earlier in the season, which reduced P uptake and to faster drying of the plow layer, particularly later in the season, which also reduced P uptake. The interaction between the PPT15 indexes and SAMDIF will be discussed later.

Tillage and planting variables   In this group, the PLOW variable decreased LEAFP linearly (Table 44), as shown by the dLEAFP/dPLOW = -0.0035, which showed that plowing in the spring (coded 1) or no-plowing (coded 2) reduced LEAFP slightly as compared to plowing in the fall (coded 0). This was likely due to the better physical conditions from fall plowing that increased the availability of P and N, as discussed in the LEAFN section.

The PLDATE variable had a linear, positive effect on LEAFP which was modified by its negative interaction with STP1 as shown by the dLEAFP/dPLDATE = 0.000891 - 0.0000134 STP1. At average STP1 (33 pp2m), the simplified derivative = 0.000449 which showed that LEAFP increased at that rate per day of delayed planting date. Delayed planting of 30 days thus increased LEAFP by 0.013%; the increase was greater at low STP1 and less at high STP1 levels. The PLDATE effect on LEAFP was similar to its effect on LEAFN except that different interactions were involved.

The partial derivative of dLEAFP/dHYCROSS = -0.000898 - 0.0000665 STP1 showed that the linear, negative response of LEAFP to HYCROSS (type of hybrid from double cross = 1 to single cross = 4) became more negative as soil P in the plow layer increased. At mean STP1 (33 pp2m), the rate of change of LEAFP to HYCROSS was -0.0031 which indicated that single-cross hybrids had about 0.009% less LEAFP than double-cross hybrids. This difference increased at higher STP1 levels. The single crosses apparently had a higher rate of P utilization than the double crosses, as suggested by this LEAFP response, and by the fact that single crosses usually yield more than double crosses.

From the PLDEN effects on LEAFP shown in Table 44, the dLEAFP/dPLDEN = -0.000304 + 0.000000364 PLDEN + 0.0000150 PPT15I - 0.000000394 PPT15Q. The curvilinear response of LEAFP to plant density was modified by the interaction between this variable and the PPT15 indexes. Examination of the simplified derivatives with respect to the PPT15 indexes at two PLDEN levels (Table 50) showed that increasing PPT15 had a greater positive effect and over more of the 75-day period at higher PLDEN than at the lower PLDEN levels. Conversely, the negative effect on LEAFP of PLDEN decreased as precipitation in the 5-day periods increased. The simplified derivative, at mean values of PPT15I = 11.20 and PPT15Q = 210.80, is dLEAFP/dPLDEN = -0.000220 + 0.000000364 PLDEN, which shows that minimum LEAFP occurred at PLDEN = 604 or, decoded, 60,400 plants/ha, which is much higher than its mean.

<u>Fertility management variables</u> The dLEAFP/dMANURE = 0.000625 - 0.00000910 STP1 showed that the linear, positive response of LEAFP to MANURE decreased as soil test P in the plow layer increased, thus

suggesting that soil P substituted for the P applied in the manure. At average STP1, the simplified derivative = 0.000325 which showed that 22 MT/ha (10 T/acre) increased LEAFP by only 0.007%.

Likewise, total P (from fertilizer and manure) applied the year before (PRES1) increased LEAFP linearly but this response decreased with increased STP1 and STP2 (Table 44). The dLEAFP/dPRES1 = 0.000368 - 0.00000398 STP1 - 0.00000595 STP2. At STP1 and STP2 values of 20 and 10 pp2m P, respectively, the simplified derivative = 0.00023; at PRES1 = 40, LEAFP was increased by 0.01%. On the other hand, LEAFP increased at a decreasing rate as PRES2 (total P applied two years before) increased and it attained a maximum at PRES2 = 34.4 kg P/ha, as calculated from the dLEAFP/dPRES2 = 0.000341 - 0.00000990 PRES2.

The NCODE1 (code for crop rotation) variable had a curvilinear effect on LEAFP modified by a positive interaction with STN as shown by dLEAFP/dNCODE1 = -0.00366 + 0.0000962 NCODE1 + 0.0000119 STN. At mean STN (63 pp2m of N), LEAFP decreased at a decreasing rate, reaching a minimum at NCODE1 = 30, which corresponds to third-year corn after a meadow crop. The negative effect of NCODE1 (decreasing residual legume N) on LEAFP was decreased as soil test N in the plow layer increased, thus demonstrating once more than soil N substituted for the decreased N availability as the number of years between corn and meadow in the rotation increased, and that the higher levels of both legume and soil N also increased LEAFP.

The partial derivative of dLEAFP/dPBDCT = 0.000270 - 0.00000651 STP1 + 0.000995 SAND + 0.00000346 DCAL showed that the response of LEAFP to applied P fertilizer other than row P decreased as STP1 increased, indicating a substitution effect of soil P for applied P. The response of LEAFP to PBDCT also increased in soils with sand parent material, probably because of the lower availability of both N and P in these soils, and as DCAL increased or, decoded, as the depth to the carbonate layer decreased. At STP1 = 20 pp2m, in deep loess soils (SAND = 0), and at an average DCAL (30 cm or, decoded, 122 cm to top of calcareous layer), the slope of the linear LEAFP response to PBDCT = 0.00024, while at the same levels of these variables but in soils with sand parent material, the response was 0.00124. At STP1 = 20, SAND = 0, and DCAL = 137 (decoded, 15 cm to carbonates), the linear response to LEAFP to PBDCT was 0.00061. For the three linear responses listed, the LEAFP responses to 30 kg P/ha were 0.007%, 0.037%, and 0.018% P, respectively. These responses to PBDCT appear to be low.

The enhancing effect of NBDCT on P uptake was demonstrated by the response of LEAFP to the NBDCT variable (Table 44). The dLEAFP/dNBDCT = 0.000567 - 0.000000994 NBDCT + 0.00280 DVI - 0.00275 DVL + 0.000654 DVQ - 0.0000444 DVC - 0.000155 SAND - 0.00000327 STN - 0.00000891 PPT15I showed that the weather indexes affected the availability of applied N and, hence, its effect on LEAFP. The effects of the DV and PPT15 indexes on the LEAFP response to NBDCT were indirectly shown when discussing the effects of the weather indexes on LEAFP. In general, the applied N compensated to some degree the effects of moisture stress on LEAFP. The response of LEAFP to NBDCT decreased as precipitation increased in the 5-day periods. The negative interaction with SAND showed that the LEAFP response to NBDCT decreased in soils with sand parent material, which is not the expected response because these soils usually have lower soil N levels. The curvilinear response of LEAFP to NBDCT was also decreased as STN increased which is the expected substitution effect of soil N for applied N.

At mean values of DVI = 2.18, DVL = 11.40, DVQ = 70.47, DVC = 473.26, and PPT15I = 11.20, and with STN = 50 and SAND = 0 (deep loess soils), the simplified derivative is: 0.000131 - 0.000000994 NBDCT. Maximum LEAFP occurred at NBDCT = 132 kg N/ha. For sandy parent material, the partial derivative, holding all others at their designated levels, is: -0.000024 - 0.000000994 NBDCT. This showed LEAFP decreased with increasing NBDCT. At lower STN levels and other weather index combinations, the LEAFP responses will be positive.

<u>Soil test variables</u> The partial derivative of dLEAFP/dPH1 = 0.00414 - 0.000185 PH1 showed that LEAFP increased at a decreasing rate as PH1 increased and reached a maximum at PH1 = 7.24 (decoded), above which increased pH levels decreased LEAFP. This curvilinear response showed the dual effect that soil pH exerts on the P availability which is reduced under either low or high soil pH values. This effect was reflected by the LEAFP levels. From pH 5.5 to pH 7.24 (coded 5 to 22.4), the change in LEAFP as calculated from the partial derivative was 0.028% P.

The dLEAFP/dSTN = 0.00196 - 0.0000242 STN - 0.00000327 NBDCT + 0.0000119 NCODE1 showed that, at NBDCT = 125 kg N/ha and NCODE1 = 30 (third-year corn after meadow), LEAFP increased at a decreasing rate as STN increased and attained a maximum at STN = 79 pp2m N, which is a medium-high level. The interactions between STN and both NBDCT and NCODE1 showed the same sort of N substitution effects mentioned previously.

The relationship between LEAFP and STP1 (soil P in the plow layer) was modified by the interactions between STP1 and the variables of PBDCT, PRES1, MANURE, HYCROSS, PLDATE, PALEO, and ALLUV, as well as with the partitioned DV and PPT15 indexes (Table 44). This complex response thus indicated that the effect of soil P on LEAFP was influenced by several factors affecting its availability and its uptake.

The dLEAFP/dSTP1 = 0.00223 - 0.000401 DVI + 0.00000432 PPT15L - 0.00000651 PBDCT - 0.00000398 PRES1 - 0.00000910 MANURE - 0.0000665 HYCROSS - 0.0000134 PLDATE + 0.000733 PALEO - 0.000248 ALLUV. At mean levels of DVI = 2.18, PPT15L = -2.36, PBDCT = 9 kg P/ha, PRES1 = 13 kg P/ha, MANURE = 5 MT/ha, PLDATE = 23, and with HYCROSS = 4 or single-cross hybrid and in deep loess-derived soils (PALEO = 0 and ALLUV = 0), the simplified derivative = 0.000615 which is the rate of change of LEAFP per unit increase in STP1. As STP1 increased by 30 units, LEAFP increased about 0.02%.

This first partial derivative showed that the response of LEAFP to STP1 decreased as PBDCT, PRES1, and MANURE increased which suggested the substitution effects of applied P for soil P. The negative interaction with PLDATE showed that later corn planting, having lower yield potential, decreased the positive LEAFP response to higher soil test P levels, thus indicating their lower P utilization efficiency.

On the other hand, the interactions with the PALEO and ALLUV variables showed that the response of LEAFP to STP1 was higher in soils with a paleosol parent material but was less in soils having an alluvial parent material as compared to deep-loess-derived soils. The negative STP1*HYCROSS interaction showed that LEAFP responded less to STP1 in single-cross hybrids than in double-cross hybrids. Apparently, the single crosses had a higher soil P use efficiency because they usually outyield double-crosses.

The interactions between STP1 and the 5-day DV indexes had constant, negative coefficients for all periods (Table 45), which indicated that the responses of LEAFP to STP1 increased as the moisture stress increased (lower DV indexes). This showed that higher levels of STP1 overcame to some extent the negative effect of a soil moisture deficit.

Conversely, the interactions between STP1 and the 5-day PPT15 indexes on LEAFP had coefficients that increased linearly from negative values in periods 1 to 7 to positive values from period 9 on (Table 48). These coefficients showed that the response of LEAFP to STP1 decreased as precipitation increased in periods 1 to 7 and increased as precipitation increased in periods 9 to 15. Increased precipitation early in the season decreased LEAFP response to STP1 (probably because of more effect on available N than on available P) and late in the season increased LEAFP response to STP1 (probably because of greater P availability in a moister plow layer).

The STP2 (soil test P at a depth from 76 to 107 cm) had a positive, linear effect on LEAFP that decreased as PRES1 (total P applied the previous year) increased and increased as the depth to the layer of carbonates decreased. The dLEAFP/dSTP2 = 0.000264 - 0.00000595 PRES1 +

0.0000111 DCAL. The first interaction showed a substitution effect of residual P for subsoil P, whereas the second interaction revealed that a decreasing depth to the carbonate layer (increasing pH in the subsoil) increased the LEAFP response to higher STP2 levels. At mean PRES1 = 13 kg P/ha and DCAL = 30 cm (decoded, 122 cm to the top of the calcareous layer), LEAFP increased about 0.0005% per unit increase in STP2.

Soil variables The partial derivative of dLEAFP/dTHAHOR = 0.0000846 - 0.00001874 THAHOR + 0.00659 DVI - 0.00283 DVL + 0.000262 DVQ indicated that LEAFP increased at a decreasing rate as THAHOR increased. However, this curvilinear response and the level of THAHOR associated with maximum LEAFP were modified by the interactions with the 5-day DV indexes. The estimated regression coefficients associated with these interactions (Table 45) showed that the curvilinear response of LEAFP to THAHOR increased as DV increased (less stress) in periods 1, 2, 3, and 8, while the response decreased as DV increased in periods 4 to 7. Similar responses to this variable were observed in the case of LEAFN, thus suggesting once more the parallel behavior of these two leaf nutrients. However, it is difficult to determine if this response was due to the direct effect of THAHOR on LEAFP or was an indirect effect through the correlation between LEAFP and LEAFN.

Lower levels of LEAFP occurred in soils with paleosol parent material as compared to deep loess soils. The LEAFP increased as STP1 in the plow layer increased, as shown by the dLEAFP/dPALEO = -0.0336 + 0.000733 STP1. The opposite occurred in soils with alluvial parent material, as shown by the dLEAFP/dALLUV = 0.0128 - 0.000248 STP1. At average STP1, the simplified derivatives = -0.0094 and 0.0046, respectively.

The partial derivative of dLEAFP/dSAND = 0.0263 - 0.00348 PPT15I + 0.000129 PPT15Q - 0.000155 NBDCT + 0.000995 PBDCT showed that the linear, positive effect of SAND on LEAFP was modified by the interactions between SAND and the PPT15 indexes as well as with applied N and applied P. The estimated regression coefficients associated with the interactions between the SAND variable and the PPT15 indexes (Table 48) showed that the response of LEAFP in soils with sand parent material decreased as precipitation increased in periods 3 to 13 and increased as precipitation increased in periods 1, 2, 14, and 15. These effects were previously referred to. The interactions between SAND with NBDCT and PBDCT were opposite in signs, thus showing that the response of LEAFP to SAND decreased as applied N was increased and increased as applied P was increased.

Lastly, the DCAL variable continued to show the effect of high soil pH on the P availability, as revealed by the dLEAFP/dDCAL = -0.0000534 - 0.0000030 DCAL + 0.0000111 STP2 + 0.00000346 PBDCT. At average STP2 (18 pp2m) and PBDCT (9 kg P/ha), the simplified derivative is dLEAFP/dDCAL = 0.000178 - 0.00000300 DCAL. The LEAFP increased to a maximum at DCAL = 59 cm (or, decoded, 93 cm or 37 in. to the top of the calcarous layer) and then decreased, as was expected, because of the effect of high soil pH on available subsoil P. This curvilinear response of LEAFP to DCAL (decreasing depth to calcareous layer) increased as STP2 (subsoil test P) and PBDCT increased.

Time of sampling variable The SAMDIF (difference between silking and sampling dates) had a quadratic effect on LEAFP which was modified by its interactions with the DV and PPT15 indexes. The dLEAFP/dSAMDIF = 0.0000184 - 0.001028 SAMDIF - 0.0396 DVI + 0.0176 DVL - 0.00165 DVQ - 0.0000943 PPT15L. The regression coefficients of the interactions between SAMDIF and the DV indexes (Table 45) showed that increasing DV (higher soil moisture) decreased the rate of change of LEAFN to SAMDIF in periods 1, 2, 3, and 8 and the opposite occurred in periods 4 to 7. On the other hand, the coefficients for its interactions with the PPT15 indexes were positive in periods 1 to 7 and negative in periods 9 to 15, as they decreased linearly from the first period to the last. Thus, the rate of change of LEAFP to SAMDIF increased with increasing PPT15 in the first seven periods and decreased in the last 7 periods.

At average levels of the DV and PPT15 summation variates, DVI = 2.18, DVL = 11.40, DVQ = 70.47, and PPT15L = -2.36, the simplified derivative = -0.00172 - 0.001028 SAMDIF showed that maximum LEAFP was reached at SAMDIF = -1.7, that is, about 1.7 days after the silking date.

Corn Leaf K Concentration

The relationships between corn leaf K concentration (LEAFK) and weather factors and their variability through the growing season, as well as with some soil and management factors, were investigated in this section. The procedures used were the same as were described for LEAFN and LEAFP in the preceding sections.

Correlation analysis of weather indexes

The same excess moisture, moisture stress, and precipitation indexes, that were computed for various time periods and related to LEAFN and LEAFP levels, were also related to the variability of LEAFK. The simple correlations between the weather indexes within these periods were shown in Table 4 and discussed in the LEAFN section. The correlation coefficients between these indexes and LEAFK are given in Table 51.

Inspection of this table shows that the correlations between the weather indexes and LEAFK were lower than those between these indexes and LEAFN (Table 4) and LEAFP (Table 29). The highest correlations were attained by the indexes in period A (42 to 22 days before leaf sampling date); in contrast, correlations between the indexes for this period and both LEAFN and LEAFP were the lowest ones. In period A, the correlations between LEAFK and the weighted or unweighted PPT indexes were higher than those with any of the moisture stress indexes. Correlations between LEAFK and weather indexes in all other periods were mostly low and nonsignificant.

As for the previous two leaf nutrients, the highly correlated DT and DW indexes attained similar correlations with LEAFK, as did the also highly correlated DV, DX, and X1 indexes. However, a comparison of the DT and DW indexes and of the DT and DX indexes revealed that weighting by energy (pan evaporation) increased the correlation of the moisture stress indexes with LEAFK, whereas weighting by growth stage gave only a small effect. Application of both weighting factors in DVA resulted in an additive effect, but in the DV indexes for the other periods, the application of the growth stage factor decreased the correlations. Similar effects

Table 51. Simple correlation coefficients between LEAFK and weather indexes for various time periods

Weather index[a]	r-value	Weather index	r-value	Weather index	r-value
DT75	-.051	DTB	-.067	PPT4	.08
DX75	.062	DXB	.036	PPT5	.02
DW75	-.065	DWB	-.077	PPT6	-.05
DV75	.042	DVB	.021	PPT7	-.06
X175	.037	X1B	.019	PPT8	-.03
PPT75	.058	PPTB	-.059		
PPT75W	.005	PPTBW	-.069	EXMO1	.01
				EXMO2	-.04
DT40	-.020	EXMO	-.022	EXMO3	-.04
DX40	.091	PPT46	.054	EXMO4	-.02
DW40	-.045			EXMO5	.01
DV40	.065	DV1	.03	EXMO6	.05
X140	.056	DV2	.01		
PPT40	.069	DV3	.11	PPTEM1	.09
PPT40W	.006	DV4	.13	PPTEM2	-.03
		DV5	.08	PPTEM3	-.02
DTA	.063	DV6	.06	PPTEM4	-.01
DXA	.112	DV7	-.01		
DWA	.070	DV8	-.01		
DVA	.127				
X1A	.130	PPT1	.09		
PPTA	.150	PPT2	.08		
PPTAW	.144	PPT3	.06		

[a]The identification of these weather indexes and the times of the periods are given in Table 2.

were noticed for the precipitation indexes.

Lastly, the early season EXMO and PPT46 indexes had no significant correlations with LEAFK, although the correlations showed opposite signs. From the weather indexes tested in the preliminary correlation analysis, the EXMO, PPT46, DV75, DVA, DVB, PPTA, and PPTB indexes were retained for further testing in alternative regressions.

The second stage of this testing included the assessment of the simple correlation coefficients between LEAFK and the eight 5-day moisture stress and precipitation indexes as well as those with the six 8-day excess moisture and the four 8-day precipitation indexes. Because of the high intercorrelations between DT and DW, among DX, DV, and X1, between the two precipitation indexes, and among the eight DT indexes (Tables 4 and 6), only the correlations between LEAFK and the 5-day DV and PPT indexes and the 8-day EXMO and PPTEM indexes are listed in Table 51.

The correlation coefficients between LEAFK and the DV indexes revealed a different pattern in the relationships than between the same indexes and LEAFN (Table 5) and LEAFP (Table 30). The coefficients between LEAFK and DV1 to DV6 were positive, being largest in periods 3 and 4, while the ones for DV7 and DV8 were nil. Hence, these suggested that LEAFK was more associated with soil moisture conditions in the third and fourth 5-day periods (22 to 32 days before silking), which could be responsible for the highest association previously shown between LEAFK and DVA.

Positive correlations between LEAFK and PPT1 to PPT4 occurred while negative ones were associated with PPT6 to PPT8 (Table 51). Thus, increased rainfall in the first half of the 40-day period before leaf sampling date increased LEAFK at sampling time, while higher amounts of rainfall in the later periods decreased it.

The simple correlation coefficients between LEAFK and the six 8-day excess moisture indexes and the four 8-day PPTEM indexes were mostly nonsignificant (Table 51). Surprisingly, precipitation in the first 8-day period (3 to 11 days after planting) appeared to be positively associated with LEAFK.

Development of the base regression model

The base model of LEAFK on selected soil and management variables was computed to investigate further the relationships between the selected weather indexes or some combinations of them and LEAFK. The procedures used were similar to those applied in the previous two sections. The variables included are listed in Table 1.

Correlation analysis The variables utilized to develop the base model for LEAFK were basically the same as the ones used in the previous two sections. Therefore, the correlations between pairs of soil and management variables were also the same as listed in Table 8.

Alternative regressions of LEAFK on linear functions of the variables shown in Table 1 were computed to delete from the pairs of highly correlated variables the ones giving the lower R^2-values. From the fertility management group, the deleted variables were PBDCT, NRES1, PRES1, and PRES3. The highly correlated, row-applied fertilizer variables (NROW, PROW, and KROW) and also the highly correlated PAWC and SAND variables were still retained for evaluation in alternative quadratic regression models.

The correlations between EROS and THAHOR, CPL and CMAX, DCAL and PHMIN, and STK1 and STK2 were also evaluated in these alternative regressions and the EROS, CMAX, PHMIN, and STK2 variables were deleted. The RL3, SL1, and CB2 variables were also deleted from further modeling because they frequently or always occur after leaf sampling.

Model selection   Alternative regressions of LEAFK on linear and squared functions of selected soil and management variables were computed to determine the most significant variates as well as to assess further the pairs of highly correlated variables still contained in the data set. These quadratic models were designated as the Model LEAFK-A series, and initially included a total of 50 linear and 43 squared functions (Table 52). The model selection steps are presented in Table 53.

Model LEAFK-A1 with 93 variates attained an R^2 of 0.635 which was reduced to 0.631 (Model LEAFK-A6) after 40 nonsignificant variates were deleted. The linear and squared variates of the BARR variable were deleted in Model LEAFK-A7 but the effect on the R^2 was nil, suggesting that the factors involved in the BARR variable were not importantly related to LEAFK variability. Hence, the factors associated with the BARR variable were more related to the factors involved in the availability, uptake, and concentration of N and, to a lesser extent, with those of P.

The variates of the DV75 and EXMO indexes were next eliminated which decreased the R^2 of Model LEAFK-A8 only slightly (Table 53). Model LEAFK-A8 became the base model and its regression statistics are given in Table 54.

Table 52. Variates included in the base regression Model LEAFK-A series

X_i	Variate	X_i	Variate	X_i	Variate
4	LEAFK	35	PAWC	66	$PLDATE^2$
		36	NCODE1	67	$ROWWID^2$
5	PLDEN			68	$MANURE^2$
6	BARR	37	HYMAT	69	$NROW^2$
7	CRW	38	HYCROSS	70	$PROW^2$
8	CB1			71	$KROW^2$
9	WEEDS	39	TWP	72	$NBDCT^2$
10	CULT	40	RANGE	73	$KBDCT^2$
11	PLOW			74	$TILE^2$
12	TILLAFT	41	THAHOR	75	$KCODE^2$
13	PLDATE	42	DRAIN	76	$KRES1^2$
		43	CPL	77	$PRES2^2$
15	PLMETH	44	DCMAX	78	$SLOPE^2$
16	ROWWID	45	BIO	79	$ROWSLP^2$
17	MANURE			80	$PH1^2$
18	NROW	46	LOESS/T	81	STN^1
19	PROW	47	TILL	82	$STP1^2$
20	KROW	48	PALEO	83	$STK1^2$
21	NBDCT	49	SAND	84	$DV75^2$
22	KBDCT	50	COLLUV	85	$EXMO^2$
23	TILE	51	ALLUV	86	$PAWC^2$
24	KCODE			87	$NCODE1^2$
25	KRES1	52	DPHMIN	88	$HYMAT^2$
26	PRES2	53	DCAL	89	$HYCROSS^2$
		54	STP2	90	TWP^2
27	SLOPE	55	SAMDIF	91	$RANGE^2$
28	ROWSLP			92	$THAHOR^2$
		58	$PLDEN^2$	93	$DRAIN^2$
29	PH1	59	$BARR^2$	94	CPL^2
30	STN	60	CRW^2	95	$DCMAX^2$
31	STP1	61	$CB1^2$	96	BIO^2
32	STK1	62	$WEEDS^2$	97	$DPHMIN^2$
		63	$CULT^2$	98	$DCAL^2$
33	DV75	64	$PLOW^2$	99	$STP2^2$
34	EXMO	65	$TILLAFT^2$	100	$SAMDIF^2$

Table 53. Model selection steps to derive the base model for LEAFK, Model LEAFK-A series

Model no.	No. of variates	Identification	R^2
LEAFK-A1	93	Complete model, all variates listed in Table 52	.635
A2 to A6	81 to 53	Deleted 40 nonsignificant linear and squared variates stepwise from Model LEAFK-A1	.635 to .631
A7	51	Deleted BARR, $BARR^2$ from Model LEAFK-A6	.630
A8	46	Final model, deleted DV75, $DV75^2$, EXMO, and $EXMO^2$ from Model LEAFK-A7	.625

Testing of weather indexes

The final base model for LEAFK was employed to further test the weather indexes that were selected by the previous correlation analysis. These indexes were added either individually or in selected combinations to the base model and were evaluated by the improvement in the R^2-values of the resulting regression models. This testing included three stages.

First stage of testing In this stage, the EXMO, PPT46, DV75, DVA, DVB, PPTA, and PPTB indexes were added to the base model. These alternative regressions were designated as the Model LEAFK-B series and their descriptions and R^2-values are given in Table 55.

Only the PPTA variable increased the R^2 appreciably above that of the base model; addition of others along with PPTA had only slight additive effects on the R^2-values (Table 55). As was also revealed by the simple

Table 54. Regression statistics of the base model of LEAFK on selected variates, Model LEAFK-A8[a]

X_i	Variate	b_i	X_i	Variate	b_i
5	PLDEN	0.000237*	42	DRAIN	-0.00206**
7	CRW	-0.00612**	43	CPL	-0.0129*
9	WEEDS	-0.000240*	44	DCMAX	0.000941**
11	PLOW	0.0612++	45	BIO	0.0250**
12	TILLAFT	0.00991*			
15	PLMETH	0.0310*	46	LOESS/T	0.0718*
			47	TILL	0.0555*
17	MANURE	0.00829**	48	PALEO	0.215**
20	KROW	0.00113++	50	COLLUV	0.0979*
21	NBDCT	0.0000964	51	ALLUV	0.113**
22	KBDCT	0.00103**			
			52	DPHMIN	0.00506*
23	TILE	0.00130*	54	STP2	0.00429**
24	KCODE	-0.00109*			
25	KRES1	0.00161**	55	SAMDIF^2	0.00341
26	PRES2	0.000928*	64	PLOW^2	-0.0456*
			68	MANURE^2	-0.000146*
27	SLOPE	0.0294**	72	NBDCT^2	-0.00000319*
28	ROWSLP	-0.00936*	76	KRES1^2	-0.00000667*
			78	SLOPE^2	-0.00123**
29	PH1	0.00234	80	PH1^2	-0.000207
30	STN	0.00472	81	STN^2	-0.0000459
32	STK1	0.00520**	83	STK1^2	-0.00000464**
			89	HYCROSS^2	-0.0141
36	NCODE1	-0.00144++	94	CPL^2	0.000313**
38	HYCROSS	0.0877++	97	DPHMIN^2	-0.0000437*
			99	STP2^2	-0.0000483**
41	THAHOR	-0.00236**			

[a]Intercept = 0.866** and R^2 = 0.625.

Table 55. R^2-values of the alternative regressions of LEAFK on the base model and selected weather indexes, Model LEAFK-B series

Model no.	Variables[a]	R^2
LEAFK-B1	Base model[b]	.625
B2	Base model + EXMO	.625
B3	+ DV75	.629
B4	+ EXMO + DV75	.630
B5	+ EXMO + DVA	.626
B6	+ EXMO + DVB	.627
B7	+ EXMO + PPTA	.647
B8	+ EXMO + PPTB	.626
B9	+ EXMO + DVA + DVB	.628
B10	+ EXMO + PPTA + PPTB	.648
B11	+ PPT46 + DV75	.631
B12	+ PPT46 + DVA	.631
B13	+ PPT46 + DVB	.630
B14	+ PPT46 + PPTB	.630
B15	+ EXMO + PPTA + DVA	.649
B16	+ EXMO + PPTB + DVB	.627
B17	+ EXMO + PPTA + PPTB + DVA + DVB	.650

[a]The models included quadratic functions of the weather indexes.

[b]Base model was Model LEAFK-A8 (Table 54) with R^2 = 0.625 and 46 variates.

correlation between LEAFK and PPTA, rainfall occurring in period A (20 days from 42 to 22 days before leaf sampling date) was most associated with the variability in LEAFK.

Second stage of testing The PPT and DV indexes that were computed for the eight 5-day periods in the 40-day period before leaf sampling as well as the 8-day excess moisture and precipitation indexes were also evaluated by the improvement of the R^2 when added either alone or in selected combinations to the base model. These alternative regressions were designated as the Model LEAFK-C series. Table 56 shows how these indexes were added to the base model and the R^2-values of the resulting regressions.

Comparison of the R^2 of the alternative models in Table 56 showed that the PPT1 to PPT8 indexes had the largest effect on explaining LEAFK, increasing the R^2 from 0.625 (base model) to 0.655 in Model LEAFK-C2. The quadratic effects of the PPT indexes increased the R^2 only slightly above their linear effects. Added to the PPT indexes, one group at a time, the PPTEM, DV, and EXMO index groups increased the R^2 slightly to 0.664, 0.661, and 0.660, respectively. Inclusion of all four groups of weather indexes in the model increased the R^2 only slightly more to 0.671 (Model LEAFK-C17).

Until now, the effects on LEAFK of individual weather indexes have not been discussed because no selection of the significant variates has been performed. Therefore, nonsignificant variates were deleted from Models LEAFK-C9, -C15, and -C17. From this selection, Models LEAFK-C18, -C19, and -C20 were obtained, respectively.

These models are not shown here but it was found that Model LEAFK-C18 contained the linear variates of the PPTEM2 to PPTEM4 indexes and of the PPT1 to PPT5 indexes, plus the squared variates of the PPTEM2 and PPT3 indexes. Model LEAFK-C19 included the same linear variates as the previous model, the linear and squared variates of the PPTEM1 index, the squared variate of PPT3, and the linear variates of DV3 and DV4. Model LEAFK-C20 contained the same linear variates as Model LEAFK-C19, except

Table 56. R^2-values of the alternative regressions of LEAFK on the base model and selected weather indexes, Model LEAFK-C series

Model no.	Variables (base model plus following weather variables)[a]	No. of weather indexes	R^2
LEAFK-C1	PPT1 to PPT8 (linear variates)	8	.652
C2	PPT1 to PPT8	16	.655
C3	DV1 to DV8 (linear variates)	8	.628
C4	DV1 to DV8	16	.633
C5	PPT1 to PPT8 + DV1 to DV8	32	.661
C6	PPTEM1 to PPTEM4	8	.634
C7	EXMO1 to EXMO6	12	.635
C8	PPTEM1 to PPTEM4 + EXMO1 to EXMO6	20	.641
C9	PPTEM1 to PPTEM4 + PPT1 to PPT8	24	.664
C10	EXMO1 to EXMO6 + PPT1 to PPT8	28	.660
C11	PPTEM1 to PPTEM4 + EXMO1 to EXMO6 + PPT1 to PPT8	36	.666
C12	PPTEM1 to PPTEM4 + DV1 to DV8	24	.644
C13	EXMO1 to EXMO6 + DV1 to DV8	28	.642
C14	PPTEM1 to PPTEM4 + EXMO1 to EXMO6 + DV1 to DV8	36	.649
C15	PPTEM1 to PPTEM4 + PPT1 to PPT8 + DV1 to DV8	40	.669
C16	EXMO1 to EXMO6 + PPT1 to PPT8 + DV1 to DV8	44	.665
C17	PPTEM1 to PPTEM4 + EXMO1 to EXMO6 + PPT1 to PPT8 + DV1 to DV8	52	.671
C18	Reduced model, deleted nonsignificant variates from Model LEAFK-C9	10	.663
C19	Reduced model, deleted nonsignificant variates from Model LEAFK-C15	14	.666
C20	Reduced model, deleted nonsignificant variates from Model LEAFK-C17	12	.666
C21	Reduced model, deleted nonsignificant variates at 5% level from Model LEAFK-C20	10	.665

[a]Except where indicated, models included quadratic functions of the weather indexes; base model is Model LEAFK-A8 (Table 54) with 46 variates and $R^2 = 0.625$.

for the PPTEM1 variates and, in addition, contained the linear variate of the EXMO1 index.

Because some of the variates in Models LEAFK-C18 to -C20 were significant only at the 10% level, these models were further reduced by deleting nonsignificant variates at the 5% level. After this selection, the linear variates of the PPTEM2 to PPTEM4 and of the PPT1 to PPT5 indexes were retained in all models, while only the linear variate of the DV4 index was retained from Models LEAFK-C19 and -C20. The linear EXMO1 variate was also deleted from Model LEAFK-C20. The regression statistics of the weather variates in Model LEAFK-C21 are listed in Table 57.

Examination of Model LEAFK-C21 showed that the PPTEM2 to PPTEM4 indexes had negative effects on LEAFK, while the 5-day precipitation indexes, PPT1 to PPT5, were all positively related to LEAFK with only PPT3 showing a curvilinear effect. This association of LEAFK with the precipitation occurring in the first 25 days of the 40-day period before leaf sampling agrees with the positive correlation between LEAFK and the PPTA index (Table 51). Only DV4 of the moisture stress indexes had an expected positive effect on LEAFK.

The variability in LEAFK was mostly related to rainfall occurring in the period commencing 11 days after planting to about 15 days prior to leaf sampling. These responses are explained by the results of Hanway (1962b) who reported that corn took up most of its K early in the season and that the uptake occurred at a very rapid rate. He reported that, at silking time, the corn plant had accumulated 75% of the total K, while at the same time, it had only 50 and 65% of the total N and P, respectively.

Table 57. Regression statistics of the selected weather index variates in Model LEAFK-C21[a]

Variate	b_i	Variate	b_i
PPTEM2	-0.0145**	PPT1	0.0149*
PPTEM3	-0.0226**	PPT2	0.0376**
PPTEM4	-0.0219**	PPT3	0.0749**
		PPT4	0.0609**
DV4	0.480**	PPT5	0.0221**
		$PPT3^2$	-0.0104**

[a]Intercept = 0.758** and R^2 = 0.665.

He also pointed out that, in a 2-week period, starting 38 days after emergence, the plant took up 38% of the total season's uptake of K, thus confirming that K uptake occurs mainly early in the season, although it continues at a slower rate thereafter. Hence, the weather factors prevailing in the early part of the growing season affect the availability and uptake of K and, consequently, its leaf concentration at sampling time, as demonstrated by the relationships revealed in this evaluation.

LEAFK was markedly associated with the precipitation, negatively in the period from 11 to 35 days after planting and then positively in the first 25 days of the 40-day period before leaf sampling. Excess moisture and moisture stress indexes were not clearly related to LEAFK as were the precipitation indexes.

The negative responses to PPTEM2, PPTEM3, and PPTEM4 can be due to the effect of increasing rainfall which caused poor aeration conditions that restricted the uptake of K (Lawton, 1945; Phillips and

Kirkham, 1962; Shalhevet and Zwerman, 1962). Besides, Shapiro et al. (1956) pointed out that decreased K uptake as a result of low soil oxygen may be because of decreased translocation rather than decreased absorption by the roots.

The positive effects of the PPT1 to PPT5 indexes on LEAFK agree with Jenne et al. (1958) who reported that nonirrigated corn plants had less K at tasseling than corn plants with adequate moisture supply. Likewise, Voss (1962) reported that the number of stress days were negatively related to leaf K. However, Voss (1969) found in western Iowa that leaf K decreased as soil moisture increased in the period from 6 weeks before to 3 weeks after silking; this effect may have been a dilution effect because of greater uptake of N and P under more favorable moisture conditions.

Because high soil moisture conditions are more likely to occur early in the season while soil moisture stress occurs from the middle of the season on in Iowa, the responses to the precipitation indexes are logical. Surprisingly, the excess moisture indexes, which were intended to represent the aeration conditions in the soil, were not consistently related to LEAFK; neither were the moisture stress indexes which were intended to account for the daily soil moisture balance. In their place, the precipitation indexes, which do not account for the effects of preceding events, were best related to LEAFK. An explanation of this association may be that rainfall represents the moisture conditions of the soil plow layer, which is the most important layer for determining the K uptake and leaf concentration. Again, the partitioning of the growing season into various intervals showed the differential effects of weather indexes on the leaf nutrient level.

Third stage of testing In this stage, the summation variates of a third-order polynomial representing the linear and squared functions of the 5-day PPT, PPT15, and DV indexes, as well as those for the PPT*DV interactions, were tested in alternative regressions similar to those computed for LEAFN and LEAFP. These models were designated as the Model LEAFK-D series and their description and respective R^2-values are presented in Table 58.

Models LEAFK-D1 to -D4 showed that the summation variates of the 5-day PPT indexes increased the R^2 more than those of the DV indexes. Addition of the squared functions of the 5-day PPT and DV indexes increased the R^2 only slightly. The summation variates of the PPT indexes thus had the dominant effect on LEAFK. Other alternative regression models in Table 58 showed that the DV indexes, the interactions between the PPT and DV indexes, the inclusion of seven additional precipitation periods, and the EXMO index gave little to no gain in the R^2 as compared to the PPT indexes. Replacing the EXMO index by three excess moisture indexes and the four PPTEM indexes increased the R^2 in Model LEAFK-D8 by only 0.8%.

Except for the dominant effect of the PPT indexes, the effects of the various indexes or their combinations were rather slight. However, these models were computed for two purposes: first, to verify if the summation technique yielded comparable results to those obtained by including the variates of the individual 5-day PPT and DV indexes and,

Table 58. R^2-values of the alternative regression models of LEAFK on the summation variates of a third-order polynomial of the 5-day DV, PPT, and PPT15 indexes and other indexes, Model LEAFK-D series

Model no.	Variables (base model plus following weather variables)[a]	No. of weather indexes	R^2
LEAFK-D1	LPPT	4	.651
D2	LPPT + QPPT	8	.653
D3	LDV	4	.626
D4	LDV + QDV	8	.631
D5	LPPT + QPPT + LDV + QDV	16	.657
D6	LPPT + QPPT + LDV + QDV + IPPTDV	20	.660
D7	LPPT + QPPT + LDV + QDV + IPPTDV + EXMO[b]	22	.660
D8	LPPT + QPPT + LDV + QDV + EXMO12 + EXMO34 + EXMO56 + PPTEM1 to PPTEM4	34	.668
D9	LPPT15 + QPPT15	8	.655
D10	LPPT15 + QPPT15 + LDV + QDV	16	.660
D11	LPPT15 + QPPT15 + LDV + QDV + EXMO12 + EXMO34 + EXMO56	22	.663
D12	Reduced model, deleted nonsignificant weather variates from Model LEAFK-D5	14	.657
D13	Reduced model, deleted nonsignificant weather variates from Model LEAFK-D11	13	.662
D14	Reduced model, deleted DV summation variates from Model LEAFK-D13	6	.656

[a]Symbols of summation variates are described in Table 3; L, Q, and I are the four summation variates of a third-order polynomial representing the linear, squared, and interaction functions of the 5-day weather indexes, respectively; base model LEAFK-A8 (Table 54) with 46 variates and $R^2 = 0.625$.

[b]Linear and squared functions of the EXMO and PPTEM indexes were included in the models.

second, to determine if the assumed order of the polynomial was adequate to describe the responses of LEAFK to the PPT and DV indexes during the periods of the growing season they represented.

The effects on LEAFK of the 5-day PPT and DV indexes were obtained by applying a procedure similar to the one followed for LEAFN. That is, the first derivatives of LEAFK with respect to each of the PPT and DV indexes were calculated from Model LEAFK-C5, which included the individual 5-day PPT and DV indexes, and from Model LEAFK-D5, which included the summation variates for the same indexes. The rates of change were obtained by substituting the average values of each index in their respective derivatives.

Figure 9 presents the rates of change of LEAFK with respect to each DV index that were calculated from the estimated (dashed line) and from the directly observed (solid line) regression coefficients. This figure reveals that the rates evaluated from the estimated coefficients tended to follow the same trend as the ones from the directly observed coefficients, although a noticeable discrepancy occurred in the rates for DV7. The variability of these responses across the 40-day period was not as logical as that observed when these indexes were related to the variability of LEAFN and LEAFP. However, the responses to LEAFK calculated from the estimated regression coefficients approached those from the directly observed ones with reasonable precision. This can be explained by the fact that the summation variates described the variability of the responses of LEAFK to those indexes across the 40-day period before leaf sampling despite their significance or association with LEAFK. Some of

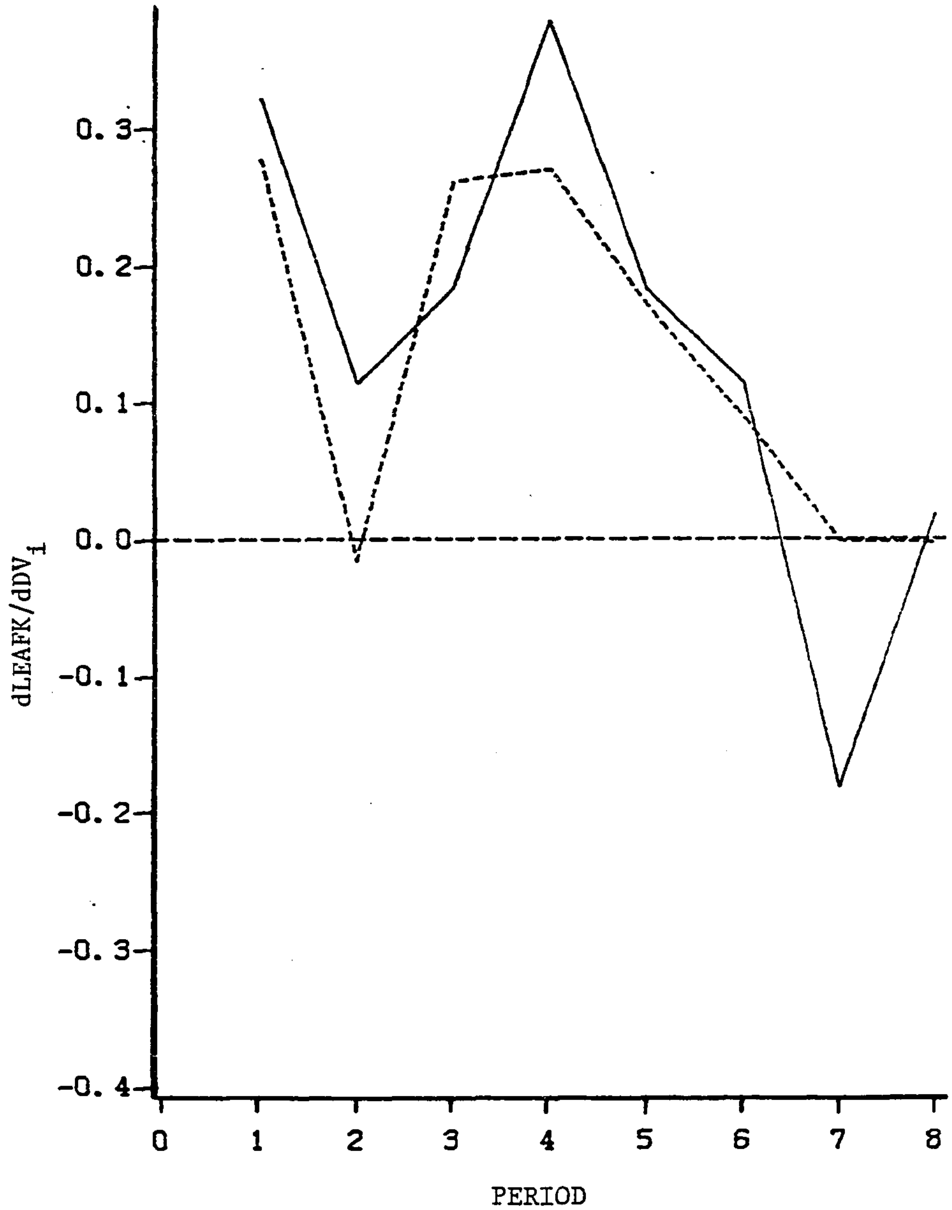

Figure 9. Rates of change of LEAFK with respect to each 5-day DV index as calculated from the directly observed regression coefficients (solid line) and from the estimated regression coefficients (dashed line)

the responses to the DV indexes in Figure 9 may result from random variability rather than from a systematic one, as demonstrated by the selection of only one 5-day index (DV4) in final Model LEAFK-C21 (Table 57).

Likewise, Figure 10 shows the close relationship between the rates of change in LEAFK with respect to the PPT indexes as calculated from the estimated coefficients and from the directly observed ones.

It was assumed that a third-order polynomial would represent the variability of the rates of change of LEAFK with respect to each 5-day PPT and DV index. To check for the proper order of the polynomial, Model LEAFK-D5 was reduced by deleting the nonsignificant variates at the 10% level. The regression statistics of the resulting Model LEAFK-D12 are given in Table 59.

All eight summation variates of the third-order polynomial representing both the linear and squared functions of the DV indexes were significant. This appears to disagree with the responses of LEAFK to the DV indexes that were revealed in reduced Model LEAFK-C21 (in which only the DV4 index was significant). However, this is because the summation variates represent the variability of the rates of change of LEAFK to the DV indexes, regardless of the significance of such responses, as previously discussed. Therefore, the variability shown in Figure 9 due to the DV indexes was described by the third-order polynomial.

Finally, the summation variates of the third-order polynomial representing the linear effects of the PPT indexes were significant, but only the PPTQL and PPTQQ variates for the squared functions of these indexes were significant, thus indicating that the trend shown in Figure 10 was

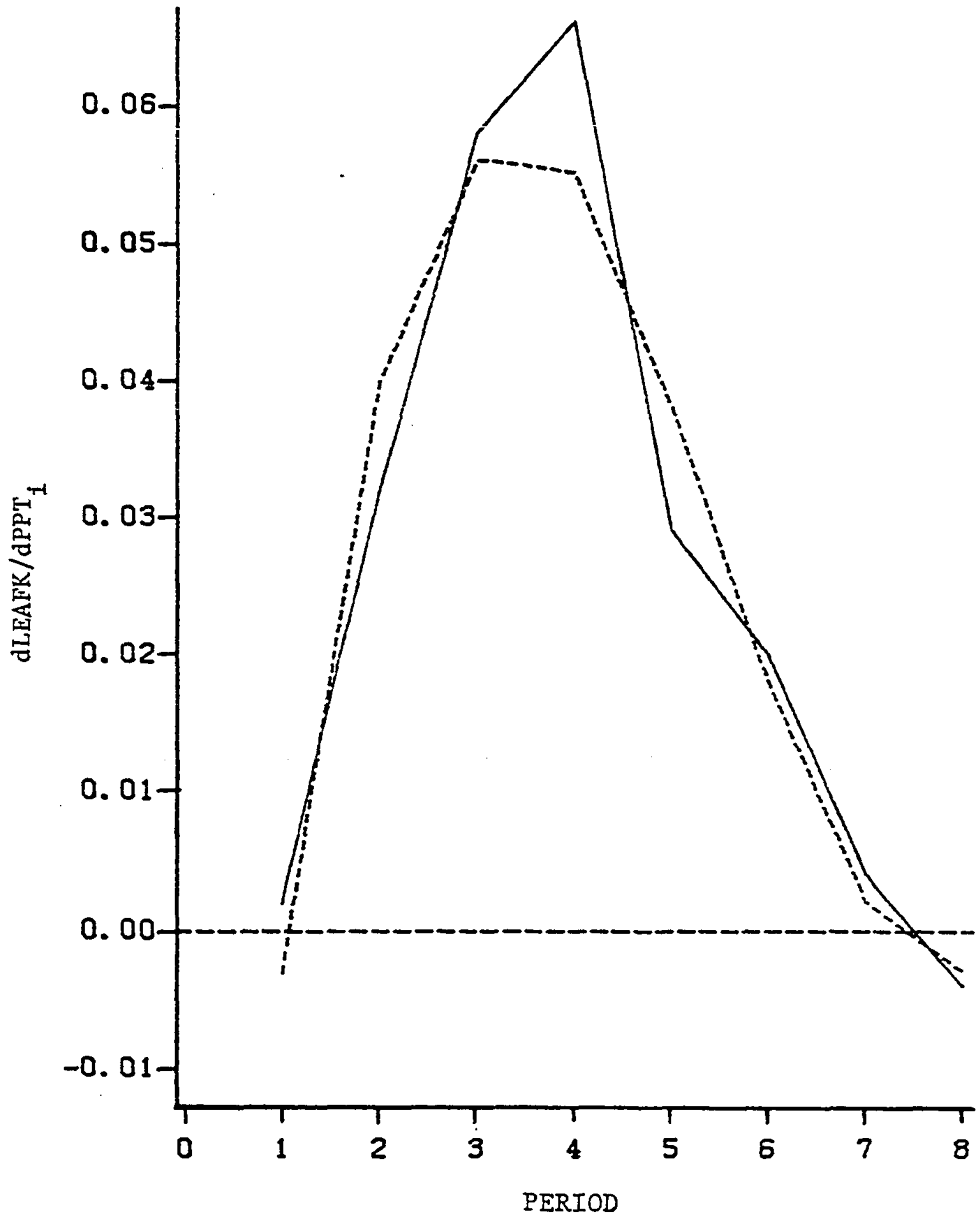

Figure 10. Rates of change of LEAFK with respect to each 5-day PPT index as calculated from the directly observed regression coefficients (solid line) and from the estimated regression coefficients (dashed line)

Table 59. Regression statistics of the summation variates for the DV and PPT indexes in reduced Model LEAFK-D12[a]

X_i	Variate	b_i	X_i	Variate	b_i
9	DVI	4.030*	17	PPTI	-0.05375**
10	DVL	-3.305**	18	PPTL	0.08325**
11	DVQ	0.7170**	19	PPTQ	-0.01814**
12	DVC	-0.0468**	20	PPTC	0.001064**
13	DVQI	-10.218++	21	PPTQI	-
14	DVQL	8.262*	22	PPTQL	-0.002461*
15	DVQQ	-1.7424**	23	PPTQQ	0.0003385*
16	DVQC	0.1098**	24	PPTQC	-

[a]Intercept = 0.877 and R^2 = 0.657.

also represented by a third-order polynomial.

A stepwise, backward elimination of the nonsignificant summation variates of the PPT15 and DV indexes was also carried out on Model LEAFK-D11 to derive a base model to be used in the next stage and Model LEAFK-D13 was obtained. This model included the summation variates of a third-order polynomial for the linear and squared functions of the DV indexes as well as the third-order summation variates for the linear functions of the PPT15 indexes. Surprisingly, the linear and squared variates of the EXMO12 index were highly significant in this model.

On the basis that the previous testing of the weather indexes showed that the DV indexes were not importantly related to LEAFK and that the summation variates of the DV indexes, although significant, were describing nonsignificant responses, the summation variates of the DV indexes were deleted from further modeling and Model LEAFK-D14 was obtained.

This model still included the EXMO12 index whose linear and squared variates were highly significant. It should be noticed that the NCODE1 variable was deleted from the base model because it was coded similarly to the KCODE variable; it had been erroneously retained up to this point.

Testing of the interactions

Model LEAFK-D14 was used as the base model for the subsequent testing of a number of interactions between weather indexes and some soil or management variables, as well as for testing, in a second stage, the interactions between some variables of the soil and management group. The selected variates of weather, soil, and management variables in this base model are presented in Table 60.

A procedure similar to the one used in the previous two sections was followed for this testing. Four series of regression models were computed that were the Model LEAFK-E to Model LEAFK-H series. Table 61 shows the interactions that were tested in each series.

In the four series of models, 72 interaction variates were tested, of which only 6 were retained in final Model LEAFK-H5 which had an R^2 of 0.667. These interactions were between the summation variates of the PPT15 indexes and the CRW, SLOPE, STK1, and KBDCT variables. None of the 16 interactions between the EXMO12 index and other variables was significant. The inclusion of the 6 interaction variates increased the R^2 by only 1.1% as compared to that of the base model. Thus, the responses of LEAFK to the selected soil and management variables were little modified by the interactions involving the weather indexes investigated in this study.

Table 60. Base set of variates included in the regression models to select interaction variates, Model LEAFK-D14[a]

X_i	Variate	X_i	Variate	X_i	Variate
1	EXMO12	25	TILE	42	TILL
		26	KCODE	43	PALEO
10	PPT15I	27	KRES1	44	COLLUV
11	PPT15L	28	PRES2	45	ALLUV
12	PPT15Q				
13	PPT15C	29	SLOPE	46	DPHMIN
		30	ROWSLP	47	STP2
14	SAMDIF				
		31	PH1	48	$SAMDIF^2$
15	LEAFK[b]	32	STN	49	$PLOW^2$
		33	STK1	50	$MANURE^2$
16	PLDEN			51	$NBDCT^2$
17	CRW	35	HYCROSS	52	$KRES1^2$
18	WEEDS			53	$SLOPE^2$
19	PLOW	36	THAHOR	54	STN^2
20	TILLAFT	37	DRAIN	55	$STK1^2$
		38	CPL	56	CPL^2
21	MANURE	39	DCMAX	57	$DPHMIN^2$
22	KROW	40	BIO	58	$STP2^2$
23	NBDCT			59	$EXMO12^2$
24	KBDCT	41	LOESS/T		

[a]Intercept = 0.890** and R^2 = 0.656.

[b]LEAFK was the dependent variable regressed on the listed variates plus selected interaction variates.

Next, three additional series of alternative regressions were computed to ascertain the effects on LEAFK of some interactions between variables of the soil and management group. Table 62 presents the interactions that were tested in the Models LEAFK-I to Model LEAFK-K series.

The model selection steps applied in each series are given in Table 63. In the three series of models, 49 interaction variates were

Table 61. Interaction variates tested in multiple regression Models LEAFK-E to LEAFK-H series[a]

X_i	Model LEAFK-E	X_i	Model LEAFK-F	X_i	Model LEAFK-G	X_i	Model LEAFK-H
76	PPT15I*CRW	82	PPT15I*KBDCT	83	PPT15I*KCODE	87	PPT15I*DRAIN
77	PPT15L*	83	PPT15L*	84	PPT15L*	88	PPT15L*
78	PPT15Q*	84	PPT15Q*	85	PPT15Q*	89	PPT15Q*
79	PPT15C*	85	PPT15C*	86	PPT15C*	90	PPT15C*
80	PPT15I*SLOPE	86	PPT15I*PLDEN	87	PPT15I*CPL	91	PPT15I*WEEDS
81	PPT15L*	87	PPT15L*	88	PPT15L*	92	PPT15L*
82	PPT15Q*	88	PPT15Q*	89	PPT15Q*	93	PPT15Q*
83	PPT15C*	89	PPT15C*	90	PPT15C*	94	PPT15C*
84	PPT15I*STK1	90	PPT15I*KRES1	91	PPT15I*DCMAX	95	PPT15I*SAMDIF
85	PPT15L*	91	PPT15L*	92	PPT15L*	96	PPT15L*
86	PPT15Q*	92	PPT15Q*	93	PPT15Q*	97	PPT15Q*
87	PPT15C*	93	PPT15C*	94	PPT15C*	99	PPT15C*
88	PPT15I*PALEO	94	PPT15I*THAHOR	95	EXMO12*KRES1	100	EXMO12*ROWSLP
89	PPT15L*	95	PPT15L*	96	*THAHOR		
90	PPT15Q*	96	PPT15Q*	97	*KCODE		
91	PPT15C*	97	PPT15C*	99	*WEEDS		
92	EXMO12*CRW	99	EXMO12*KBDCT	100	*MANURE		
93	*SLOPE	100	*PLDEN				
94	*STK1						
95	*PALEO						
96	*DRAIN						
97	*CPL						
99	*DCMAX						
100	*TILE						

[a]Variate 98 was a dummy variable in all series.

Table 62. Interaction variates tested in multiple regression Models LEAFK-I, LEAFK-J, and LEAFK-K series[a]

X_i	Model LEAFK-I	X_i	Model LEAFK-J	X_i	Model LEAFK-K
75	KCODE*STK1	75	KCODE*STK1	74	NBDCT*STK1
76	NCODE1*	76	NBDCT*	75	MANURE*
77	NBDCT*	77	MANURE*	76	PLDEN*
78	KBDCT*	78	PLDEN*	77	SLOPE*
79	KRES1*	79	SLOPE*	78	DRAIN*
80	KROW*	80	DRAIN*	79	CPL*
81	MANURE*	81	CPL*	80	BIO*
82	PLDEN*	82	BIO*	81	STP2*
83	WEEDS*	83	KCODE*KBDCT	82	TILL*
84	HYCROSS*			83	ALLUV
85	THAHOR*	84	PRES2*STK1	84	TILE*
86	SLOPE*	85	STP2*		
87	DRAIN*	86	TILL*	85	KCODE*KBDCT
88	CPL*	87	PALEO*	86	BIO*KCODE
89	DCMAX*	88	ALLUV*	87	THAHOR*
90	BIO*	89	DPHMIN*	88	LOESS/T*STK1
		90	STN*	89	COLLUV*
91	KCODE*KBDCT	91	SAMDIF*	90	PH1*
92	NCODE1*	92	TILE*	91	CRW*
93	PLDEN*			92	PRES2*STP2
94	WEEDS*	93	BIO*KCODE	93	BIO*
95	NBDCT*STN	94	THAHOR*	94	BIO*STN
		95	KROW*	95	NCODE1*
		96	CPL*		
		97	MANURE*	96	BIO*MANURE
				97	LOESS/T*
		99	SLOPE*DRAIN	99	TILL*MANURE
		100	MANURE*CPL	100	SLOPE*CPL

[a]Variate 98 was a dummy variable in Models LEAFK-J and LEAFK-K series.

Table 63. Model selection steps, Models LEAFK-I, LEAFK-J, and LEAFK-K series

Model no.	No. of X_i	Identification	R^2
LEAFK-I1		Complete model, variates in Model LEAFK-H5 plus 21 interaction variates	.682
I4		Reduced model, deleted 12 of the 21 interaction variates from Model LEAFK-I1	.681
J1		Complete model, variates in Model LEAFK-I4 plus 16 more interaction variates	.688
J3		Reduced model, deleted 12 interaction variates from Model LEAFK-J1	.686
K1		Complete model, variates in Model LEAFK-J3 plus 12 more interaction variates	.690
K10		Final model, deleted nonsignificant variates (5% level) from Model LEAFK-K1	.683

tested, of which only 4 were retained. In the last series, a stepwise, backward elimination of nonsignificant variates at the 5% level was performed and the final interaction Model LEAFK-K10 had an $R^2 = 0.683$.

The R^2-value attained in the final interaction model represented a moderate improvement of 5.8% with respect to the R^2 of the base quadratic model (Model LEAFK-A8, without weather indexes) and an improvement of 1.6% with respect to the R^2 of Model LEAFK-H5 which included weather indexes as well as their selected interactions with soil and management variables.

From the explained variability in LEAFK, 3.5% was due to the effect of the variates of the excess moisture and precipitation indexes included in the model, 1.1% was due to the effect of their interactions with soil and management variables, and 2.1% was attributed to interactions between variables of the soil and management group.

Interpretation of the final interaction Model LEAFK-K10

The regression statistics of the final interaction model, Model LEAFK-K10, are shown in Table 64. This model included 28 linear and 9 squared variates of soil and management variables, 4 summation variates of the PPT15 indexes, the linear and squared variates of the EXMO12 index, 4 variates of interactions between weather and soil and management variables, and 11 variates of interactions between variables of the soil and management group. A discussion of the effects on LEAFK of the variables included in this model follows.

Weather indexes The EXMO12 index, which represented the excess moisture conditions during the 16-day period starting 3 days after planting, increased LEAFK at a decreasing rate and reached a maximum at EXMO12 = 2.44, as calculated from dLEAFK/dEXMO12 = 0.0518 - 0.0212 EXMO12. The level of EXMO12 associated with maximum LEAFK was much larger than its mean. The reason for the positive response to this weather index is not known because the effects on LEAFK of the PPT15 indexes for about the same time interval were negative, as will be shown later in this section.

The effects on LEAFK of the 5-day PPT15 indexes were estimated by calculating the first derivatives of LEAFK with respect to each PPT15 index, as was done for LEAFN and LEAFP in the previous two sections.

Table 64. Regression statistics of the final interaction Model LEAFK-K10[a]

X_i	Variate[b]	b_i	X_i	Variate	b_i
1	EXMO12 (0.5)	0.0518**	43	PALEO (0.03)	0.132**
10	PPT15I (11.2)	0.0116**	45	ALLUV (0.1)	0.139**
11	PPT15L (-2.4)	0.00260	46	DPHMIN (35)	0.00451*
12	PPT15Q (210.8)	-0.000187	47	STP2 (18)	0.00620**
13	PPT15C (-90.2)	-0.0000731++			
			48	SAMDIF^2	-0.00392**
14	SAMDIF (0.8)	0.00882++	49	PLOW^2	-0.0532**
16	PLDEN (380)	-0.000133	52	KRES1^2	-0.00000574*
17	CRW (15)	-0.00465**	53	SLOPE^2	-0.00177**
18	WEEDS (60)	-0.000337**	54	STN^2	-0.0000649*
			55	STK1^2	-0.00000374**
19	PLOW (0.7)	0.0580*	56	CPL^2	0.000546**
21	MANURE (5)	0.00910**	57	DPHMIN^2	-0.0000410*
22	KROW (11)	0.00209**	58	STP2^2	-0.0000347*
23	NBDCT (68)	-0.000122	59	EXMO12^2	-0.0106**
24	KBDCT (12)	-0.00111			
25	TILE (6)	0.00245**	62	PPT15L*STK1	0.0000264**
26	KCODE (17)	-0.00117**	63	PPT15Q*	-0.00000160**
27	KRES1 (26)	0.00118**	64	PPT15C*	-0.000000445**
28	PRES2 (13)	0.00182**			
			69	PPT15I*KBDCT	0.000192**
29	SLOPE (4)	0.0498**			
30	ROWSLP (1.7)	-0.00960*	74	STK1*NBDCT	-0.00000232**
			75	*MANURE	-0.0000201**
31	PH1 (15)	-0.00554**	76	*PLDEN	0.00000151**
32	STN (63)	0.00912*	77	*SLOPE	-0.0000546**
33	STK1 (225)	0.00878**	78	*DRAIN	0.0000157**
			79	*CPL	-0.0000455**
35	HYCROSS (2)	0.0131*	80	*BIO	-0.000627**
36	THAHOR (34)	-0.00175**	81	*STP2	-0.0000104**
37	DRAIN (42)	-0.00512**	83	*ALLUV	-0.000271*
38	CPL (26)	-0.0175**	84	*TILE	-0.0000117*
39	DCMAX (54)	0.00118**			
40	BIO (5)	0.118**	92	STP2*PRES2	-0.0000840**

[a]Intercept = 0.418** and R^2 = 0.683.

[b]Rounded means of the variables are given in the parentheses.

The first partial derivatives are listed in Table 65. The linear components of the 5-day PPT15 indexes (shown in the first column) varied in a cubic manner over the 15 periods, as determined by their third-order function (Table 64). These partial derivatives also show that the linear rates of change of LEAFK with respect to each PPT15 index were increased or decreased by the levels of the STK1 and KBDCT variables, depending on the signs of the interactions. Over the 15 periods, the values of the coefficients for the PPT15 interactions with STK1 varied in a cubic manner whereas those of the interactions with KBDCT were constant, as shown by their interactions with the respective PPT15 summation variates in Table 64.

The mean values of each PPT15 index and of the interacting variables were substituted into the partial derivatives and the rates of change with respect to each PPT15 index were obtained and represented graphically in Figure 11. As shown in this figure, the rates of change of LEAFK to the PPT15 indexes varied cubically, decreasing from a negative rate of change to PPT15-1 to a minimum to PPT15-3, then increasing to a maximum, positive rate of change to PPT15-11, and then decreasing again to a negative rate of change with respect to the PPT15-15 index. Thus, these responses indicated that rainfall during the first 30-day period after planting (PPT15-1 to PPT15-6) was negatively related to LEAFK and this effect coincided with the negative responses of LEAFK to the PPTEM2, PPTEM3, and PPTEM4 indexes (Table 57), although it was opposite to the response of LEAFK to the EXMO12 index, as mentioned previously. The positive rates of change to PPT15 in periods 7 to 14 suggested that

Table 65. First partial derivatives of LEAFK on each 5-day PPT15 index calculated from the regression coefficients in Model LEAFK-K10

$\frac{dLEAFK}{dPPT15-i}$ [a]	First partial derivatives
PPT15-1	= 0.00930 - 0.000126 STK1 + 0.000192 KBDCT
PPT15-2	= 0.00505 - 0.000130 STK1 + 0.000192 KBDCT
PPT15-3	= 0.00304 - 0.000122 STK1 + 0.000192 KBDCT
PPT15-4	= 0.00288 - 0.000106 STK1 + 0.000192 KBDCT
PPT15-5	= 0.00409 - 0.0000828 STK1 + 0.00192 KBDCT
PPT15-6	= 0.00624 - 0.0000560 STK1 + 0.000192 KBDCT
PPT15-7	= 0.00889 - 0.0000276 STK1 + 0.000192 KBDCT
PPT15-8	= 0.01161 + 0.0000000 STK1 + 0.00012 KBDCT
PPT15-9	= 0.01395 + 0.0000244 STK1 + 0.000192 KBDCT
PPT15-10	= 0.01548 + 0.0000432 STK1 + 0.000192 KBECT
PPT15-11	= 0.01575 + 0.0000540 STK1 + 0.000192 KBDCT
PPT15-12	= 0.01434 + 0.0000544 STK1 + 0.000192 KBDCT
PPT15-13	= 0.01080 + 0.0000420 STK1 + 0.000192 KBDCT
PPT15-14	= 0.00470 + 0.0000144 STK1 + 0.000192 KBDCT
PPT15-15	= -0.00442 - 0.0000308 STK1 + 0.000192 KBDCT

[a] First partial derivatives with respect to each PPT15 index, where i = 1, 2, ..., 15.

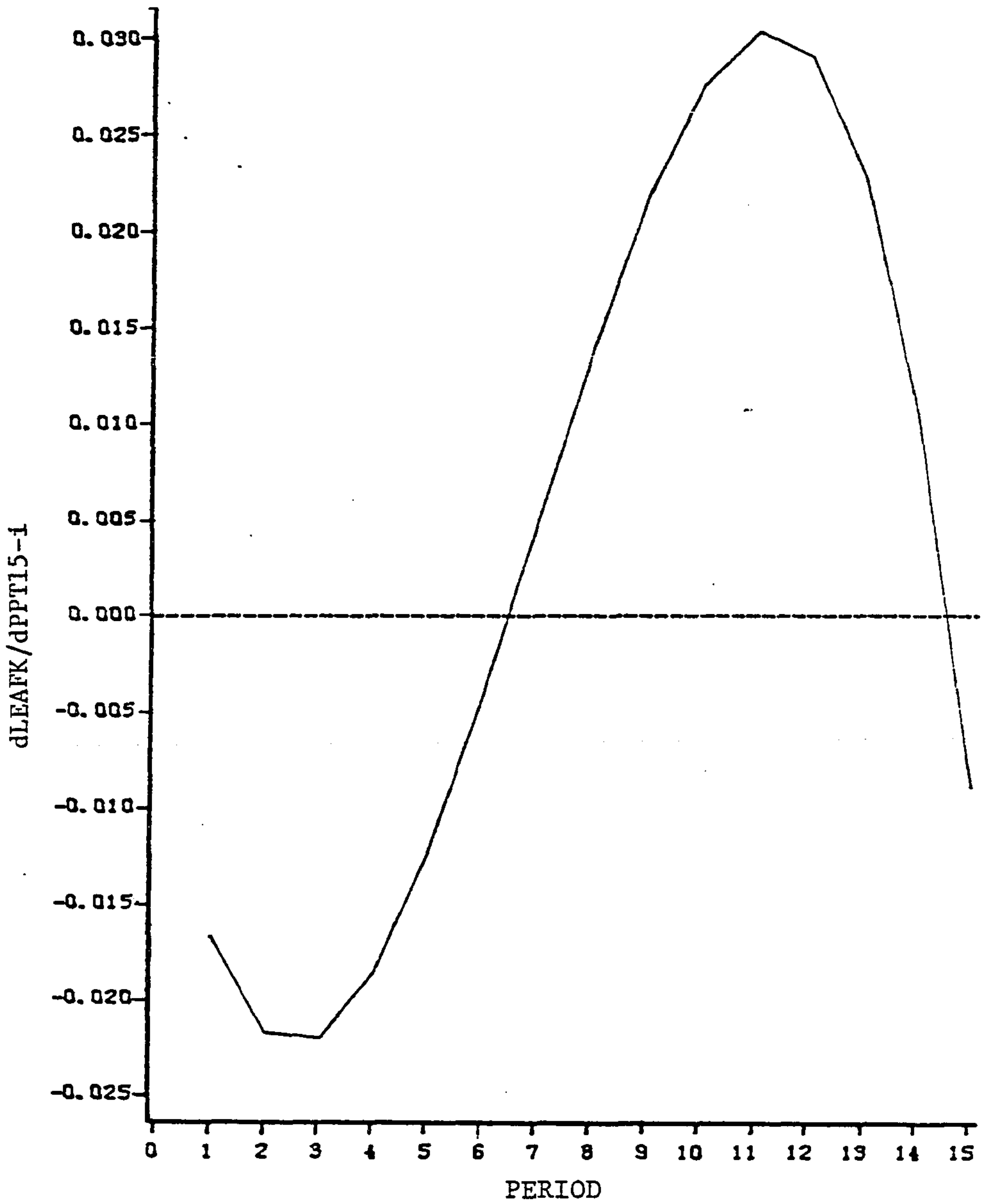

Figure 11. Rates of change of LEAFK with respect to each 5-day PPT15 index at average values of all variables in the first partial derivatives (Table 65)

rainfall in these periods was positively related to LEAFK.

To illustrate the interactions between the PPT15 indexes and STK1, the first partial derivatives (Table 65) were simplified for values of STK1 of 75 and 300 pp2m of K and KBDCT was set constant at a rate of 12 kg K/ha (mean).

First, the estimated regression coefficients associated with the interactions between the PPT15 indexes and STK1 (Table 65) showed that in periods 1 to 7 and 15, the linear responses of LEAFK to the respective PPT15 indexes decreased with increased levels of STK1, while in periods 9 to 14, the rates of change of LEAFK increased as STK1 increased. These effects are apparent in Figure 11.

The distributions of the rates of change of LEAFK across the 15 periods at both levels of STK1 are shown in Figure 12. In periods 1 to 7 and at the low level of STK1, the rates of change of LEAFK to the corresponding PPT15 indexes were higher than those for the high levels of STK1, whose rates of change were negative in all but in period 7. Hence, these responses suggested that precipitation in the first half of the 75-day period decreased LEAFK, particularly if soil test K in the plow layer was high. This probably was due to the development of poor aeration conditions that restricted K uptake and LEAFK if STK1 was high but not as much at low STK1 because LEAFK was much nearer the minimum level.

On the other hand, in periods 9 to 14, higher rates of change occurred at the high level of STK1. This suggested that, with a high level of soil test K, an increase in soil moisture increased K uptake

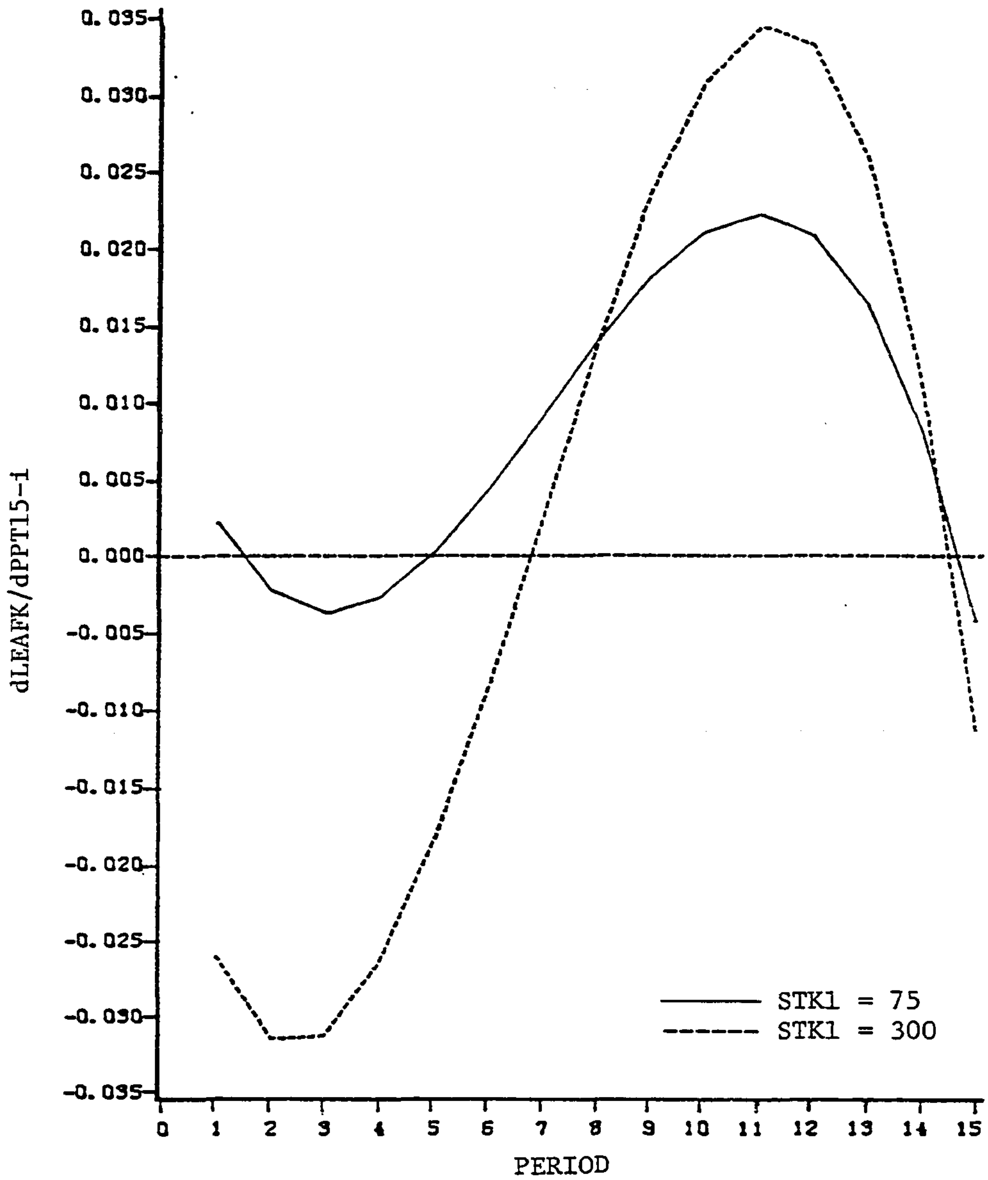

Figure 12. Rates of change of LEAFK with respect to each 5-day PPT15 index at two levels of soil test K in the plow layer (STK1)

and LEAFK which is the expected response at this stage of the growing season when moisture stress frequently occurs in Iowa.

The estimated regression coefficients associated with the interactions between the PPT15 indexes and KBDCT (Table 65) were the same and positive over all 15 periods, as determined by the interaction of KBDCT with the PPT15I variate. These interactions showed that higher responses to precipitation occurred if the levels of KBDCT (applied K other than K row) increased. Although the average STK1 was high in this study, these interactions showed positive responses to applied K, particularly under increased rainfall, which indicated that luxury consumption of K occurred under adequate soil moisture conditions.

The responses of LEAFK to the PPT15 indexes and to the cited interactions showed that the availability of soil K for plant uptake was related to soil factors determining available K, mostly soil test K in the plow layer and applied K, as well as to the soil moisture conditions as determined by the rainfall occurring during the season.

Environmental variables The partial derivatives dLEAFK/dCRW = -0.00465 and dLEAFK/dWEEDS = -0.000337 showed that increased levels of these variables decreased LEAFK linearly. Hence, as the root system was damaged by corn rootworms or competition for K uptake occurred between corn and weeds, LEAFK decreased.

Tillage and planting variables The dLEAFK/dHYCROSS = 0.0131 indicated that, as the hybrid changed from double to single crosses, LEAFK increased linearly. The single-cross varieties had about 0.04% more LEAFK than the double-cross varieties. This response was opposite to that of LEAFN and LEAFP to this variable, probably because of the often-referred negative relationship between LEAFK and those two leaf nutrients.

The ROWSLP (slope of the rows) decreased LEAFK at a rate given by the dLEAFK/dROWSLP = -0.00960, which showed that LEAFK decreased about 0.10% as the slope of the rows increased from 0 to 10%. This suggested that higher infiltration rates and/or better fertility conditions of soils in contoured fields increased LEAFK as compared to those planted up and down the hill.

The partial derivative of dLEAFK/dPLOW = 0.0580 - 0.1064 PLOW showed that maximum LEAFK occurred at coded PLOW = 0.5. This maximum occurred between fall plow (coded 0) and spring plow (coded 1). There was no difference between fall and spring plowing, but for not plow (coded 2), LEAFK was 0.10% less than for the other two.

The dLEAFK/dPLDEN = -0.000133 + 0.00000151 STK1 showed that the plant density effect on LEAFK varied as the soil test K in the plow layer increased. At STK1 levels of 100 (low) and 300 pp2m (high), the rates of change were 0.000018 and 0.00032, respectively, which were increases in LEAFK of 0.002 and 0.032 per increase of 10,000 plants/ha. This positive response may be an accumulation effect on LEAFK as N and P became deficient as plant density increased, as shown by the negative effects of PLDEN on LEAFN and LEAFP. This positive response of LEAFK to PLDEN was reported by Voss (1969) and by Dumenil and Hanway (1965).

Fertility management variables The KROW and KCODE variables increased and decreased LEAFK linearly (Table 64) at rates given by dLEAFK/dKROW = 0.00209 and dLEAFK/dKCODE = -0.00117, respectively. These responses showed that LEAFK increased about 0.06% with a row application of 30 kg K/ha and that LEAFK was about 0.07% less in corn after 2 or more years of meadow or silage (coded 60) as compared to continuous corn (coded 0).

The partial derivative of dLEAFK/dMANURE = 0.00910 - 0.0000201 STK1 showed that the linear response of LEAFK to MANURE decreased with increased soil test K levels. At low STK1 (100 pp2m of K), the rate of change was of 0.0071 which showed that 22 MT/ha increased LEAFK by 0.16%. However, soil K substituted for K in the manure as shown by the negative interaction between these two variables.

The NBDCT variable had a negative, linear effect on LEAFK and a negative interaction with STK1 (Table 64). The dLEAFK/dNBDCT = -0.000122 - 0.00000232 STK1. At average STK1 (225 pp2m of K), the simplified derivative = -0.000644; application of 150 kg N/ha decreased LEAFK about 0.10%. This response suggested that a dilution effect occurred as better plant growth was promoted by increased NBDCT and at higher levels of soil K. Dumenil and Hanway (1965) and Tyner and Webb (1946) reported that N fertilizer usually decreased LEAFK.

The dLEAFK/dTILE = 0.00245 - 0.0000117 STK1. At STK1 = 100 and 300 pp2m, the rates of change of LEAFK with respect to TILE (distance to tile, coded 61 - distance in m) were 0.00128 and -0.00106, respectively, which showed that LEAFK increased or decreased with increased distance to the tile line, depending on the STK1 level. These effects reflect the changing relative availabilities of K with respect to N and P at various STK1 levels due to better drainage.

Fertilizer K other than row K (KBDCT) had a negative, linear effect on LEAFK which was modified by its interaction with the PPT15 indexes, as shown by the dLEAFK/dKBDCT = -0.00111 + 0.000192 PPT15I. At mean PPT15I of 11.20, the simplified derivative = 0.00104 which showed that application of 60 kg K/ha increased LEAFK about 0.06%. The regression coefficients associated with the interactions between KBDCT and the precipitation indexes were the same and positive over the 15 periods (Table 65), thus showing that increased precipitation increased the response of LEAFK to applied K.

The partial derivative of dLEAFK/dPRES2 = 0.00182 - 0.0000840 STP2. At STP2 = 40 (deep loess, prairie soils in eastern Iowa), the rate of change was -0.00154. The application of 40 kg P/ha two years before the present season decreased LEAFK about 0.06%. Subsoil P had a substitution effect for applied P.

The total K applied (from fertilizer and manure) the year before (KRES1) increased LEAFK at a decreasing rate to the maximum LEAFK at KRES1 = 103 kg K/ha, as calculated from dLEAFK/dKRES1 = 0.00118 - 0.0000115 KRES1.

<u>Soil test variables</u> From this group of variables, the PH1 (soil pH in the plow layer) variable decreased LEAFK linearly at a rate given by the dLEAFK/dPH1 = -0.00554. From pH 5.5 to 7.5 (coded 5 to 25), LEAFK decreased about 0.11%.

On the other hand, soil test N in the plow layer had a quadratic effect on LEAFK. The dLEAFK/dSTN = 0.00912 - 0.000130 STN indicated that

LEAFK increased to a maximum at STN = 70 pp2m of N, which is a level slightly higher than its mean.

The LEAFK was also quadratically related to subsoil P (STP2) and this effect was modified by PRES2 (level of total P applied two years before). The dLEAFK/dSTP2 = 0.00620 - 0.0000694 STP2 - 0.0000840 PRES2. At PRES2 = 20 kg P/ha, the simplified derivative = 0.00452 - 0.0000694 STP2 and maximum LEAFK occurred at STP2 = 65 pp2m of P, a level found in transition or forest deep-loess soils.

The quadratic effects of both STN and STP2 suggest that a balance exists between the two soil nutrients and LEAFK. Initially, if both soil N and soil P are low, LEAFK increases as they increase, but if soil N and soil P are at high levels, LEAFK thus decreases as they increase. This is likely due to the increased plant growth caused by higher levels of available N and P which results in a dilution effect on LEAFK.

Clearly, the highest association between LEAFK and the variables included in this study was that between LEAFK and soil test K in the plow layer. This was revealed by their high correlation (r = 0.63), by the t-values of the regression coefficients of the STK1 linear and squared variates (15.3 and 14.5, respectively), as well as by the magnitudes of the standard partial regression coefficients (3.05 and 0.94, respectively) which were the highest of all. Hence, STK1 explained most of the variability in LEAFK. Besides, the importance of this variable was also evidenced by its numerous interactions with other variables (Table 64).

The dLEAFK/dSTK1 = 0.00878 - 0.00000748 STK1 + 0.0000264 PPT15L -

0.00000160 PPT15Q - 0.000000445 PPT15C - 0.00000232 NBDCT - 0.0000201 MANURE + 0.00000151 PLDEN - 0.0000546 SLOPE + 0.0000157 DRAIN - 0.0000455 CPL - 0.000627 BIO - 0.0000104 STP2 - 0.000271 ALLUV - 0.0000117 TILE. As shown by this derivative, the curvilinear effect of STK1 on LEAFK decreased as applied N other than row N (NBDCT), subsoil test P (STP2), and manure application increased. Likewise, higher levels of soil fertility usually associated with prairie-derived soils (BIO) decreased the responses of LEAFK to soil test K. Also, lower responses to STK1 occurred in alluvial soils which have higher subsoil K levels. Conversely, the curvilinear response of LEAFK to STK1 was increased as PLDEN increased, as explained previously.

The curvilinear responses of LEAFK to STK1 were importantly modified by variables related in some way to the soil moisture condition, as revealed by the interactions between STK1 and the variables of SLOPE, CPL, DRAIN, and TILE. The curvilinear effect of STK1 on LEAFK decreased as the slope and the clay percentage of the plow layer increased, and as the distance to the tile line decreased and as the coded natural internal drainage class increased (drainage became poorer).

As discussed in the weather index subsection, the rates of change of LEAFK to STK1 were decreased by increased precipitation in the time interval from about planting to 30 days after, hence, demonstrating the negative effect of high soil moisture conditions on LEAFK, likely due to poor aeration conditions that decreased K uptake. Thereafter, increased precipitation levels were mostly associated with positive rates of change of LEAFK to soil K, thus, suggesting the beneficial effect of rainfall in a stage in which the water balance is usually negative.

At mean levels of PPT15L = -2.36, PPT15Q = 210.80, and PPT15C = -90.18, NBDCT = 100 kg N/ha, MANURE = 0, PLDEN = 550 (55,000 plants/ha), SLOPE = 5, DRAIN = 40 (moderately well-drained), CPL = 30%, BIO = 3 (forest-prairie transition), STP2 = 50 pp2m, ALLUV = 0, and TILE = 0, the simplified derivative = 0.00561 - 0.00000748 STK1. Maximum LEAFK occurred at STK1 = 750 pp2m, a very high value. The change in LEAFK as STK1 increased from 100 (low) to 300 (high) pp2m of K, as computed from the simplified derivative and for the given conditions, was 0.82% K.

Soil variables The THAHOR and DCMAX variables were linearly related to LEAFK. The dLEAFK/dTHAHOR = -0.00175 and the dLEAFK/dDCMAX = 0.00118 gave the respective rates of change of LEAFK with respect to these variables. The negative effect of THAHOR on LEAFK can be related to a dilution effect because of the better plant growth that occurs in deeper soils which usually have better fertility and soil water storage conditions. The positive effect of DCMAX (depth to maximum clay horizon) is difficult to explain because it is highly intercorrelated with several soil variables (Pena-Olvera, 1979), as explained in the LEAFN section.

The SLOPE variable had a quadratic effect on LEAFK which was modified by its negative interaction with STK1 (Table 64). The dLEAFK/dSLOPE = 0.0498 - 0.00354 SLOPE - 0.0000546 STK1. At mean STK1 (225 pp2m of K), the simplified derivative = 0.0375 - 0.00354 SLOPE and maximum LEAFK occurred at SLOPE = 10.6%, higher than expected because lower STK and STK2 levels occur in soils on the more level landscape positions and on the steeper, more eroded positions.

Likewise, the CPL variable had a quadratic effect on LEAFK that was modified by its interaction with STK1. The dLEAFK/dCPL = -0.0175 + 0.00109 CPL - 0.0000455 STK1. At average STK1, the simplified derivative = -0.0277 + 0.00109 showed that minimum LEAFK was associated with CPL = 25.4%. This response was unexpected because maximum LEAFK was expected in the 25-35% range of clay in the plow layer. Low clay soils or sandy soils at one extreme and high clay soils and associated poor drainage at the other extreme generally have lower STK1 levels than soils with moderate clay levels. Intercorrelations involving CPL, DRAIN, and other variables may be distorting the coefficients for the CPL variable. The simple correlation between CPL and DRAIN ($r = -0.48$), however, was high but not excessively so.

The partial derivative dLEAFK/dDRAIN = -0.00512 + 0.0000157 STK1. At STK1 = 100 (low), the rate of change of LEAFK with respect to DRAIN was of -0.00355. From well drained = 30 to poorly drained = 70, the decrease in LEAFK was 0.14%. Higher STK1 levels decreased the adverse effects that poorer drainage had on LEAFK through the positive STK1*DRAIN interaction.

The responses of LEAFK to the five previous soil variables, in addition to its responses to the TILE and PPT15 variables, showed that the K availability, uptake, and leaf concentration were closely related to factors influencing the soil moisture conditions, particularly those prevailing in the soil plow layer.

The dLEAFK/dBIO = 0.118 - 0.000627 STK1. At STK1 = 100 pp2m, the linear response = 0.055 which showed that LEAFK was about 0.22% more in prairie-derived soils (BIO = 5) as compared to LEAFK in forest-derived soils (BIO = 1). As STK1 increased to 188 pp2m of K, the difference between the prairie and the forest soils decreased to 0. Most of the BIO comparisons were from eastern Iowa where average STK1 was considerably less than in western Iowa.

The PALEO variable had a linear, positive effect on LEAFK, as shown by the dLEAFK/dPALEO = 0.132. It had negative effects on LEAFN and LEAFP. Conversely, the linear effect on LEAFK of the ALLUV variable was modified by the level of STK1, as shown by the dLEAFK/dALLUV = 0.139 - 0.000271 STK1. The positive ALLUV effect on LEAFK decreased with increased STK1 up to 513 pp2m of K.

Lastly, the DPHMIN (depth to midpoint of horizon with minimum pH) had a quadratic effect on LEAFK, as shown by the dLEAFK/dDPHMIN = 0.00451 - 0.0000820 DPHMIN, which indicated that maximum LEAFK occurred at DPHMIN = 55 cm, with all other variables constant. As DPHMIN increased above 55 cm, as is common in more highly leached and acid soils in eastern Iowa, LEAFK was decreased.

Time of sampling variable The partial derivative of dLEAFK/dSAMDIF = 0.00882 - 0.00784 SAMDIF showed that maximum LEAFK occurred at SAMDIF = 1.1, that is, one day before the estimated 75% silking date. From SAMDIF = 1.1, the LEAFK was about 0.06% less if sampled 4 days before or after this date. This curvilinear effect was different from expected. Hanway (1962b) reported that loss of K from the leaves occurred prior to silking in two plots, whereas it occurred immediately after silking in the other two plots and then continued to maturity. However, much of the K was apparently translocated to and accumulated in the stalks.

Contrary to what was observed with LEAFN and LEAFP, weather factors did not influence the responses of LEAFK to the SAMDIF variable. This probably is because most of the K uptake occurred early in the season, as reported by Hanway (1962b); hence, weather conditions prevailing later near or at the sampling time are less likely to affect the uptake of K and its leaf concentration.

SUMMARY AND CONCLUSIONS

Plant analysis has been used as a tool to diagnose the nutritional status of crops to determine their fertilizer requirements. However, many researchers have recognized that plant nutrient composition varies with the variability of soil, climate, time, plant, management, and other factors. Hence, this variability prevents an accurate interpretation of plant analysis results if these relationships remain unidentified.

In this study, data collected from 1961 to 1970 in 15 Iowa counties representing most major soil association areas were used. The N, P, and K concentrations (LEAFN, LEAFP, LEAFK, respectively) of the corn leaf sampled around silking time were related to weather factors and their variability through the growing season and to selected soil and management factors using 1927 observations.

The objectives of this research were: (1) to determine the correlations among weather indexes computed for various periods of the growing season and between them and the corn leaf N, P, and K concentrations; (2) to test and select in a series of quadratic models the most significant soil and management factors related to the leaf nutrient concentrations; (3) to test selected weather indexes for various periods of the growing season in the presence of quadratic functions of selected soil and management factors for each of the leaf nutrients; (4) to assess the usefulness of a summation technique to relate weather indexes computed for continuous subdivisions of the growing season to the variability in the leaf nutrients in the presence of the soil and management factors; (5) to test and select the most significant interactions between the weather indexes and other variables on the leaf nutrients; and (6) to select a final multiple regression model with interactions for predicting each of the corn leaf N, P, and K concentrations.

A soil moisture program, as modified by Pena-Olvera (1979), was used to compute moisture stress, excess moisture, and precipitation indexes for various periods of the growing season or subdivisions of some of these periods. The computed moisture stress indexes, as designated by Henao (1976), were: DT (unweighted index), DX (weighted by a pan evaporation factor), DW (weighted by a growth stage factor), DV (weighted by both pan evaporation and growth stage), and X1 (weighted by an evaporation factor from the Shaw (1963) relationship).

The periods for which the moisture stress indexes were computed were: (1) from 42 days before to 33 days after the leaf sampling date, (2) from 42 to 2 days before the leaf sampling date, (3) from 42 to 22 days before the leaf sampling date, and (4) from 22 days to 2 days before the leaf sampling date. These indexes were designated by adding to Henao's symbols the 75, 40, A, and B symbols, respectively. Subsequently, the same indexes were computed for the eight 5-day intervals in the 40-day period before leaf sampling date. These indexes were designated by adding to Henao's symbols the numbers 1 to 8, for the corresponding 5-day period.

An excess moisture index (EXMO) was computed for the 46-day period from 3 days to 49 days after planting. Excess moisture indexes were also computed for the six 8-day intervals in the period from 3 days to 51 days after the planting date (EXMO1 to EXMO6). Two consecutive excess moisture indexes were also summed to obtain EXMO12, EXMO34, and EXMO56.

Precipitation indexes (weighted by growth stage or unweighted) were also obtained by summing the amounts of rainfall in the various periods (designated with the PPT symbol plus the symbol indicating the corresponding period) for which the moisture stress and excess moisture indexes (PPT46 and PPTEM indexes) were computed. Besides, seven additional 5-day precipitation indexes were computed to account for a total of fifteen 5-day periods covering the 75-day period up to 2 days before leaf sampling date. These indexes were the PPT15-1 to PPT15-15 indexes.

A summation technique, as proposed by Hendricks and Scholl (1943), was applied to the 5-day DV, PPT, and PPT15 indexes to obtain summation variates for a third-order function that describes the change with time of the regression coefficients associated with the linear and squared variates of each of the 5-day indexes and those of the PPT*DV interactions.

To develop the final regression model for each leaf nutrient concentration, four steps were used. First, the correlations among the different indexes and between them and LEAFN, LEAFP, and LEAFK were computed. Second, the most significant soil and management variables for each leaf nutrient were selected in a stepwise, backward procedure (10% level) to develop a quadratic base model for each leaf nutrient.

In the third step, the selected weather indexes or combinations of them were tested in three stages. The first stage included the testing of the weather indexes computed for the 75-day, 40-day, and two 20-day periods, the second stage included the 5-day DV and PPT and the 8-day EXMO and PPTEM indexes, and the third stage included the summation variates of the 5-day DV, PPT, and PPT15 indexes. The weather indexes were evaluated by the improvement of their R^2-values in alternative models. Also, in the third stage, the summation technique was evaluated by comparing the responses of each leaf nutrient to the 5-day PPT and DV indexes as calculated from a model including the individual 5-day indexes and from a model including their summation variates. The order of the polynomial was additionally checked by deleting the nonsignificant summation variates by stepwise, backward elimination.

Fourth, a second base model including selected weather indexes and selected soil and management variables was obtained and used to test the interactions between weather indexes and some soil and management variables, as well as between variables of the soil and management group. The final interaction model for each leaf nutrient was obtained by stepwise, backward elimination of nonsignificant variates at the 5% level.

The results of this study were presented in three sections that corresponded to each of the three leaf nutrients.

Corn Leaf N Concentration

The correlations between LEAFN and the various indexes for the first four periods (75-day, 40-day, and two 20-day periods) showed that soil moisture conditions occurring just prior to the time of leaf sampling were more associated with LEAFN than those occurring earlier in the season. The 46-day EXMO index was negatively correlated with LEAFN while PPT46 was less but positively correlated with LEAFN.

The correlations among the eight 5-day DV indexes were moderate to high, while those between the eight 5-day PPT indexes were very low. Also, very low correlations were found between the PPT and the DV indexes; therefore, both indexes can be included in the same model with little distortion of their regression coefficients. The correlations between the 5-day DV indexes and LEAFN were negative for the first two periods and positive in the other periods, whereas the 5-day PPT indexes were positively correlated with LEAFN.

Low correlations were also found among the 8-day early-season excess moisture and precipitation indexes and between them and the 5-day PPT and the DV indexes. Thus, all four indexes could be included in the same model to characterize the effects on LEAFN of weather factors occurring from planting to the leaf sampling time. The EXMO2 to EXMO5 indexes were negatively and significantly correlated with LEAFN; however, the 8-day PPTEM indexes were little associated with LEAFN.

Next, a base quadratic model of LEAFN on selected soil and management variables was developed to further test selected weather indexes. The final model of LEAFN on 46 variates (Model LEAFN-A9) had an R^2 of 0.370.

The first stage of the testing of the weather indexes showed that the DV moisture stress index for the 20-day period just prior to leaf sampling time explained as much variability in LEAFN as those for longer periods. The PPT index gave a similar R^2 as the DV index in the 20-day period but about 2% higher in the 40-day period. Combinations of indexes in the same model gave only slight increases in the R^2-values.

Each of the 5-day DV and PPT indexes increased the R^2 of the base model about 4%; the combination of both indexes in the same model increased the R^2-value by 7.6%. In the previous stage, the combination of the DV and PPT indexes gave only a slight increase in the R^2 over those for each index alone. Thus, this suggested that the DV indexes computed over longer periods can include opposite and counteracting effects; therefore, when partitioned into small periods, the differential effects of moisture stress can be identified and the general relationship can be improved. Partitioning of the PPT indexes did not improve the relationship with LEAFN, likely because their effects were in the same direction across the 40-day period.

The early-season 8-day EXMO and PPTEM indexes explained less variability in LEAFN than the 5-day PPT and DV indexes and, when combined with the latter indexes, only slight increases in the R^2-values occurred.

Deletion of nonsignificant variates of the 5-day and 8-day indexes included in the same model showed that excess moisture and precipitation occurring from about 19 days to 43 days after planting had negative effects on LEAFN, probably because excess moisture conditions caused losses of N by leaching and denitrification.

The DV1 index had a negative effect on LEAFN over most of its range, which showed that high soil moisture at this time still decreased available N. The DV3 to DV5 and the PPT3 to PPT8 indexes showed mostly positive relationships with LEAFN. Some of these indexes increased LEAFN linearly. Others increased it at a decreasing rate, thus showing that increased soil moisture increased N uptake and LEAFN to a certain point and then decreased both, probably because of leaching of available N from the root zone.

The selected 5-day and 8-day weather indexes in final Model LEAFN-C20 increased the R^2 about 12% with respect to that of the base model.

The testing of the summation variates of the DV and PPT indexes in alternative models showed that inclusion of the variates for the third-order function of their linear and squared components increased the R^2 by 4.9% and 5.7%, respectively, with respect to the base model. Both indexes in the same model increased the R^2 by 9.8%. Inclusion of the summation variates of the PPT*DV interactions had little effect on the R^2 as did the three 16-day excess moisture indexes and the four 8-day PPTEM indexes.

A comparison of the rates of change of LEAFN with respect to each of the 5-day PPT and DV indexes, as calculated from the directly observed regression coefficients and from the estimated regression coefficients from the summation variates, indicated a very good degree of precision. Thus, this summation technique can be useful to describe the effects on LEAFN of weather indexes computed for continuous subdivisions of the growing season.

Deletion of the nonsignificant summation variates of the DV and PPT indexes from the model including both indexes showed that the third-order summation variates of the linear and squared components of the 5-day DV indexes and of the linear components of the 5-day PPT indexes were significant, while only the linear summation variate of the squared components of the PPT indexes was significant.

A similar selection was performed in a model including the EXM012, EXM034, and EXM056 indexes, as well as the third-order summation variates of the DV and PPT15 indexes, to derive a second base model for the subsequent testing of interactions.

Four series of regression models were computed to test a number of interactions between weather indexes and soil and management variables. Also, two additional series of models were computed to test selected interactions between variables of the soil and management group. After a final stepwise, backward elimination of nonsignificant variates at the 5% level, Model LEAFN-J24 was obtained which had 76 variates and an R^2 of 0.419. This model explained about 15% more variability in LEAFN than the base Model LEAFN-A10. Although the R^2 was only 42%, a significant improvement was observed by recognizing the differential effects of weather factors occurring through the growing season on LEAFN, particularly in the period before leaf sampling date. Hence, an important understanding of the relationships between LEAFN and the weather factors was achieved.

Final Model LEAFN-J24 included 25 linear and 8 squared variates of soil and management variables, the linear and squared variates of the EXM034 index, 6 and 4 summation variates of the DV and PPT15 indexes, respectively, 16 and 9 interactions between summation variates of the DV and PPT15 indexes with other variables, respectively, 2 interactions between the EXM034 index with other variables, and 4 interactions between variables of the soil and management group. The most important effects of the variables on LEAFN will be presented briefly in the following paragraphs.

The EXMO34 index decreased LEAFN at a decreasing rate but its detrimental effect on LEAFN decreased as the levels of DCMAX (depth to maximum clay horizon) and PLDEN (plant density) increased.

The rates of change of LEAFN with respect to the 5-day DV indexes varied across the 40-day period before leaf sampling, as determined by the third-order polynomial function, and were modified by their interactions with the variables of NBDCT (applied N other than row N), WEEDS (weed infestation), NCODE1 (code for crop rotation), SAMDIF (difference between silking and sampling dates), and THAHOR (thickness of the A horizon). The initial slopes at the intercept, the magnitudes of the LEAFN responses, and the levels of each DV index associated with maximum or minimum LEAFN were affected by these complex interactions.

The DV*NBDCT interactions showed that increased DV (less moisture stress) early in the 40-day period decreased LEAFN but this response became less negative as NBDCT increased. Higher levels of DV3 to DV6 (higher soil moisture) generally were required to maximize LEAFN at low than at high NBDCT levels. This indicated that applied N offset the adverse effects of moisture stress to some extent.

The DV*SAMDIF interactions indicated that higher soil moisture was needed in the earlier periods to maintain the maximum LEAFN as leaf sampling was delayed. In the last two 5-day periods, LEAFN increased more with better soil moisture conditions if leaf sampled early than late, seemingly due to rapid translocation of N from the leaf to the developing ear shoot.

The effects on LEAFN of the other variables interacting with the DV indexes were related to the availability of N and soil moisture as affected by weed infestation, number of years after a legume or meadow crop, and the thickness of the A horizon.

The rates of change of LEAFN with respect to the 5-day PPT15 indexes, at average levels of these indexes and of the other interacting variables, varied in a quadratic manner over the 15 periods decreasing to a minimum in period 6 and then increasing at an increasing rate. These responses were modified by the levels of the PLDEN, STN (soil test N), SAMDIF, CB1 (1st-brood corn borer), DCMAX, WEEDS, and PLDATE (planting date) variables.

In periods 4 to 12, the PPT15*PLDEN interactions showed that the levels of the PPT15 indexes associated with maximum LEAFN gradually increased over time, particularly at the high PLDEN level. This indicated that higher soil moisture levels were required at higher PLDEN levels for increased N availability.

The PPT15*STN (soil test N in the plow layer) interactions showed that loss of N by leaching or denitrification caused by higher rainfall in the period of 3 to 38 days after planting had a more adverse effect on LEAFN in soils with low STN than in those with high STN. In the 35-day period before silking, the low STN soils required more rainfall to attain maximum LEAFN, thus indicating the need of a moist plow layer for maximum availability of soil and fertilizer N to supply the increasing demands for water and N in the grand period of growth prior to silking.

Other interactions showed that higher levels of the PPT15 indexes were needed to obtain maximum LEAFN as CB1 increased; this was expected because corn borer damage to the conductive tissues decreased water and nutrient uptake, particularly if soil moisture was low. The interactions between the PPT15 indexes and the WEEDS and PLDATE variables showed that increasing weeds and later planting decreased the effects of higher PPT15 on LEAFN.

The PPT15*SAMDIF interactions showed that, in the last 7 periods, sampling prior to silking decreased the PPT15 levels required for maximum LEAFN, although the opposite effects of SAMDIF in the first 7 periods could not be explained.

The LEAFN increased linearly from drilled- to hill-planted corn (PLMETH), as BIO (biosequence) changed from forest- to prairie-derived soils, from southern to northern Iowa, and with increased MANURE and STK1 (soil test K in the plow layer), and decreased as the depth to carbonate layer (DCAL) became shallower.

Conversely, LEAFN decreased in till-derived soils (TILL), paleosols (PALEO), and alluvium (ALLUV), as compared to deep loess-derived soils. Also, LEAFN decreased linearly from early to late maturing varieties (HYMAT); thus, the N utilization efficiency of late varieties may be higher than that of early varieties with a smaller sink size. The variables of TILLAFT (tillage operations after planting), HYCROSS (type of hybrid cross), and KROW (row-applied K fertilizer) had curvilinear effects on LEAFN.

The CB1 and WEEDS variables had negative, linear effects on LEAFN which were modified by their interactions with the weather indexes that were referred to previously. The PLDEN variable decreased LEAFN linearly but this response was modified by the interactions with the PPT15 indexes, as shown previously, and by its unexpected positive interaction with the EXMO34 index.

The PLDATE variable had a positive, linear effect on LEAFN and constant, negative interactions with the PPT15 indexes. The positive responses of LEAFN to delayed planting decreased as precipitation increased in each period. Thus, the earlier planted corn had lower LEAFN, probably because of a higher rate of N utilization than later planted corn.

The THAHOR variable had an unexpected negative effect on LEAFN which was modified by interactions with the DV indexes. The effect of this variable probably was reflecting the drainage class effect because of the high correlation between THAHOR and DRAIN.

The DCMAX variable had a positive effect on LEAFN which was modified by interactions with the PPT15 and the EXMO34 indexes. This effect was difficult to explain because probably it included effects of other intercorrelated soil variables. The CPL variable had a quadratic effect on LEAFN which probably reflected its correlations with DRAIN and DCMAX and their effects on N availability and N losses by leaching and denitrification.

The NBDCT variable had a quadratic effect on LEAFN which was positive over most of its range and which increased as NCODE1 and PLDEN increased, thus indicating the higher needs for N with increased number of years from legume meadow in the rotation and increased plant density. This response decreased as STN increased, thus showing the substitution effect of soil

N for applied N. The interactions between NBDCT and the DV indexes were previously discussed. Likewise, the STN variable had a curvilinear effect on LEAFN and its interactions with the NCODE1 and NBDCT variables showed the cited substitution effects. The availability of soil N was also affected by the soil moisture of the plow layer, as indicated by the interactions between STN and the PPT15 indexes on LEAFN.

The NCODE1 variable decreased LEAFN at a decreasing rate and showed the same substitution effects with soil and applied N (STN and NBDCT). The availability of N, as affected by the number of years between meadow and corn in the rotation, was also affected by the moisture stress conditions, as mentioned previously.

Lastly, the SAMDIF (difference between silking and sampling dates) had a quadratic effect on LEAFN which was modified by interactions with the DV and PPT15 indexes. At average levels of the weather indexes, leaf sampling 4 days before or after the date of maximum LEAFN (0.6 days before silking date) decreased LEAFN about 0.10%.

Corn Leaf P Concentration

The correlations between the various weather indexes and LEAFP computed for various periods or subdivisions showed very similar patterns to those described in the LEAFN section. These indicated the parallel behavior between LEAFN and LEAFP, as shown by their correlation of $r = 0.57$.

A base quadratic model of LEAFP on selected soil and management variables was derived to further test selected weather indexes. This final Model LEAFP-A20 with 36 variates had an R^2 of 0.370.

The results of the three stages of the testing of the weather indexes showed relationships between LEAFP and the various weather indexes that were very similar to those described in the LEAFN section. In general, this testing showed that the early-season excess moisture and precipitation indexes had negative effects on LEAFP which were probably due to poor aeration conditions that restricted P availability and uptake and, indirectly, through the effects of high soil moisture on available N, as shown by the negative responses of LEAFN to these indexes.

Later, from about 27 to 2 days before leaf sampling, increased soil moisture (higher DV and PPT indexes) was related to higher LEAFP levels; however, very high soil moisture levels in this period also decreased LEAFP, probably because of reduced P availability and uptake and, indirectly, because of decreased N availability.

From a model including the third-order functions of the linear and squared components of the 5-day DV and PPT15 indexes, as well as the linear and squared variates of the EXMO index, the nonsignificant weather variates were deleted to obtain a second base model. This was used to test the interactions between the weather indexes and some soil and management variables, for which three series of regression models were computed. Three additional series of models were computed to evaluate selected interactions between variables of the soil and management group. After deleting nonsignificant variates at the 5% level, final interaction Model LEAFP-J19 was obtained which had an R^2 of 0.512 and included 75 variates.

In summary, the weather indexes explained 8.8% of the variability in LEAFP, their interactions with soil and management variables explained an additional 3.3%, while the interactions between the soil and management variables accounted for an extra 4.2% of that variability.

These results showed that the weather factors, as represented by the computed indexes, exerted a direct, significant effect on LEAFP by influencing the P availability and uptake and, to a lesser extent, an indirect effect on LEAFP through their effects on N availability.

The most important effects of the variables on LEAFP in final Model LEAFP-J19 will be discussed briefly in the following paragraphs. The EXMO index (in the 46-day period from 3 days after planting) decreased LEAFP linearly, as expected.

The responses of LEAFP to the 5-day DV indexes varied across the 40-day period before leaf sampling as described by the third-order functions of their linear and squared components. These responses were modified by interactions with THAHOR, STP1, NBDCT, and SAMDIF.

The DV*THAHOR interactions showed generally that higher DV (less stress or higher soil moisture) was required to get high or maximum LEAFP in soils with thinner than with thicker A horizons. The DV*STP1 interactions showed that, early in the 40-day period, increasing soil moisture decreased LEAFP as it had decreased the highly correlated LEAFN. In later periods, the responses of LEAFP to the DV indexes showed that increased soil moisture increased P uptake, particularly if soil test P in the plow layer was low.

The DV*NBDCT interactions affected LEAFP in a similar manner as they affected LEAFN. That is, the adverse effects of either high or low moisture conditions were offset by higher levels of applied N, showing the enhancing effect of available N on P uptake, as reported in the literature.

The PPT15*STP1 interactions showed that increased rainfall decreased LEAFP in the first half of the 75-day period and at a somewhat faster rate if STP1 was high. Probably, this effect was indirect through the rainfall effect on LEAFN. In the 30-day period before leaf sampling, increased rainfall (except at high levels) increased LEAFP, particularly if soil P was high, thus showing the need for adequate soil moisture in this critical growth period.

The interactions between the PPT15 indexes and PLDEN showed that increased rainfall increased LEAFP in the last 12 periods at high plant densities but increased LEAFP only in the last 5 periods (25 days before leaf sampling) at low plant densities. Thus, higher PLDEN changed the effects of high precipitation on LEAFP from negative to positive in the earlier growth periods because of increased evapotranspiration and water requirement of the higher plant densities.

The interactions between the PPT15 indexes and the NBDCT variable showed that increased NBDCT decreased the curvilinear responses of LEAFP to the PPT15 indexes. The interactions between SAND and the PPT15 indexes showed that more negative or less positive responses of LEAFP to these indexes occurred in soils with sandy parent materials. These effects were related to N leaching occurring early in the season and to the reduced P uptake with faster drying of the soil plow layer occurring later in these soils.

The PLOW (time of plowing) variable showed that plowing in the fall gave higher LEAFP than spring or no plowing. The PLDATE variable (delayed planting) increased LEAFP linearly, but this increase was less as STP1 increased.

The negative, linear response of LEAFP to HYCROSS indicated that single crosses had less LEAFP than double crosses, and this difference increased with higher STP1 levels. This response suggested that single crosses have a higher P utilization efficiency because they usually yield more than double crosses. The PLDEN variable decreased LEAFP at a decreasing rate but its interactions with the PPT15 indexes showed that the negative effect of PLDEN on LEAFP decreased as precipitation increased.

Of the fertility management variables, the MANURE and PRES1 (total P from manure and fertilizer applied the year before) increased LEAFP linearly, but both responses decreased as STP1 increased, thus showing that soil P substituted for applied P. Also, STP2 (subsoil test P) decreased the response of LEAFP to PRES1. The PRES2 (total P from manure and fertilizer applied 2 years before) increased LEAFP at a decreasing rate.

As expected, applied P (PBDCT) increased LEAFP linearly but this response decreased as STP1 increased, due to the substitution effect. This response to PBDCT increased in soils with sand parent material (SAND), probably because of their lower N and P availability, and as the depth to carbonates decreased, probably because of reduced P availability at higher soil pH levels.

The curvilinear response of LEAFP to NBDCT was modified by interactions with the DV and PPT15 indexes and with SAND and STN. These showed that factors affecting the availability of N also affected LEAFP. In general, applied N offset to some degree the negative effects of low soil moisture on LEAFP, whereas the interaction with STN showed the typical substitution effect. However, the negative interaction with SAND was not the expected response.

The STN effects on LEAFP and those of its interactions with NBDCT and NCODE1 showed the beneficial effect of available N on LEAFP as well as the substitution effects of these sources of N. The curvilinear response of LEAFP to PH1 (pH of the soil plow layer), in which maximum LEAFP occurred at PH1 = 7.2, showed the effect of either low or high soil pH on reduced P availability and, hence, on LEAFP.

The STP1 had a positive, linear effect on LEAFP which was modified by several interactions. The interactions with the DV indexes showed that higher STP1 overcame, to some extent, the negative effects of moisture stress. Those with the PPT15 indexes showed that rainfall early in the season decreased the LEAFP response to STP1, probably because of its effect on available N, while rainfall later in the season increased the response, probably because of higher P availability in a moister soil plow layer.

The interactions between STP1 and PBDCT, PRES1, MANURE, PLDATE, and HYCROSS on LEAFP have been referred to previously. The LEAFP also increased linearly as STP2 increased but subsoil P substituted for P applied the year before (PRES1), and this response to STP2 increased as the depth to carbonates decreased.

Increased THAHOR increased LEAFP at a decreasing rate, although this response was modified by the interactions with the DV indexes, as previously shown. The parent material variables of PALEO, ALLUV, and SAND showed diverse effects on LEAFP as compared to the deep loess-derived soils. The DCAL (depth to carbonates) variable showed the expected effect of increasing soil pH on available P and on LEAFP, as well as the substitution effects of applied P (PBDCT) and of subsoil P (STP2).

The SAMDIF (difference between silking and sampling dates) had a quadratic effect on LEAFP, but this response was modified by the interactions with the DV and PPT15 indexes. At average levels of the weather indexes, maximum LEAFP occurred about 2 days after the silking date.

Corn Léaf K Concentration

The correlations between the weather indexes for the four initial periods and LEAFK were lower than those between these indexes and LEAFN and LEAFP. The highest correlations were attained by the indexes in period A (from 42 to 22 days before leaf sampling), whereas correlations between these indexes and LEAFN and LEAFP were the lowest ones. Correlations between LEAFK and the precipitation indexes were higher than those with the moisture stress indexes. The early season indexes were not importantly associated with LEAFK.

The correlations between the 5-day DV and PPT indexes showed that LEAFK was mainly and positively associated with DV3 and DV4 and with precipitation in the first half of the 40-day period, whereas precipitation in the second half reduced LEAFK. The correlations between LEAFK and the 8-day excess moisture and precipitation indexes were mostly nonsignificant.

A base model of LEAFK on selected quadratic functions of soil and management variables was next derived. The final Model LEAFK-A8 with 46 variates had an R^2 of 0.625. The initial model testing also showed that the BARR (barren stalk) variable was not importantly related to LEAFK as it was with LEAFN and considerably less so with LEAFP.

The first stage of the testing of the weather indexes in alternative models showed that only PPTA significantly increased the R^2 above that of the base model, confirming again that rainfall in period A was the weather factor most associated with LEAFK variability.

Next, the models including the 5-day indexes indicated that the PPT indexes had the greatest effect on the R^2, increasing it 3% with respect to that of the base model. Addition of other indexes increased the R^2 only slightly.

Selection of the significant variates of the 5-day and 8-day indexes included in the same model showed that precipitation in the 11 to 35 days after planting was negatively related to LEAFK, probably due to poor aeration conditions that reduced K uptake and its leaf concentration. Then, LEAFK was positively related to precipitation in the first 25 days of the 40-day period before leaf sampling, probably because low soil moisture in the plow layer at that time restricted K uptake. The responses to the early and mid-season weather indexes can be related to the fact that most of the K uptake occurs prior to the time of silking

(Hanway, 1962b).

Models including the summation variates of the 5-day PPT and DV indexes also showed that the 5-day PPT indexes were the most importantly related to LEAFK. A comparison of the rates of change of LEAFK on each 5-day DV and PPT index, as computed from the directly observed and from the estimated coefficients of the DV and PPT indexes, showed good to very good precision between the two methods. This occurred although the effects on LEAFK of the DV indexes were mostly nonsignificant, as shown previously. These models also showed that the third-order functions of these indexes described the variability in the responses of LEAFK to these 5-day indexes.

A similar selection was performed in a model including the third-order summation variates of the DV and PPT15 indexes, as well as the quadratic functions of the 8-day EXMO indexes, to derive a second base model for the subsequent testing of interactions. This base model included the EXMO12 variates and the third-order variates of the linear components of the PPT15 indexes.

Next, four and three series of regression models were computed for the testing of interactions between the weather indexes and selected soil and management variables and between variables of the soil and management group, respectively. After deletion of nonsignificant variates at the 5% level, final interaction Model LEAFK-K10 was obtained which had 58 variates and an R^2 of 0.683. This R^2 was 5.8% higher than that of the base Model LEAFK-A8 (without weather indexes). In this model, 3.5% of the variability was due to the weather indexes, 1.1% to their interactions with other variables, and 2.1% was attributed to the interactions between variables of the soil and management group.

Final Model LEAFK-K10 included 28 linear and 9 squared variates of soil and management variables, 4 summation variates of the PPT15 indexes, the linear and squared variates of the EXM012 index, 4 variates of interactions between the PPT15 indexes and other variables, and 11 variates of interactions between variables of the soil and management group. A brief discussion of the effects of these variables on LEAFK follows.

The EXM012 index unexpectedly increased LEAFK at a decreasing rate, while the PPT15 indexes affected LEAFK differentially across the 75-day period, as described by the third-order function of their linear components. The linear effects of these indexes were only modified by interactions with STK1 (soil test K in the plow layer) and the KBDCT variables.

At average levels of these indexes and of the interacting variables, the rates of change of LEAFK on these indexes showed that increased rainfall during the first 30 days after planting decreased LEAFK, the responses then became positive and increased to a maximum in period 11, and then the positive responses decreased at an increasing rate.

The PPT15*STK1 interactions showed that increased precipitation decreased LEAFK in the first half of the 75-day period, particularly if STK1 was high but not as much at low STK1 because LEAFK was closer to the minimum level. This was probably due to poor aeration conditions that restricted K uptake. In the second half of this period, an increase in soil moisture (increased rainfall) increased K uptake and LEAFK, particularly if STK1 was high, as was expected in this stage of the growing season when moisture stress often occurs.

The PPT15*KBDCT interactions showed that higher LEAFK responses to precipitation occurred at higher KBDCT levels. Because average STK1 was high in this study, these positive interactions indicated that luxury consumption of K occurred under adequate soil moisture.

The variables of CRW, WEEDS, KCODE, ROWSLP (slope of the rows), PH1, and THAHOR decreased LEAFK linearly, while the opposite effect on LEAFK was exerted by the KROW, HYCROSS, DCMAX, and PALEO variables. The variables of PLOW, KRES1 (total K applied one year before), STN, and DPHMIN (depth to horizon with minimum pH) had quadratic effects on LEAFK showing that they increased LEAFK to a maximum and then decreased LEAFK.

The LEAFK increased at a decreasing rate with increased levels of the SLOPE and STP2 variables but the response to SLOPE decreased as STK1 increased and the response of LEAFK to STP2 decreased with increased PRES2, showing a substitution effect.

The most important effect on LEAFK was exerted by the STK1 variable, either directly or through its interactions with other variables. This variable had a quadratic effect on LEAFK; the LEAFK response to STK1 decreased with increased levels of NBDCT, MANURE, SLOPE, CPL, BIO, STP2, ALLUV, and TILE, and increased as PLDEN and DRAIN increased.

The variables of MANURE, TILE, BIO, and ALLUV increased LEAFK linearly but these responses were influenced by the interactions with STK1 cited previously. The variables of NBDCT, DRAIN, and PLDEN decreased LEAFK linearly but these responses were also modified by the cited interactions with STK1.

The quadratic effects of STN and STP2 showed that at low levels of these variables, LEAFK increased as they increased; if STN and STP2 were high, LEAFK decreased as they increased, thus showing that a balance existed between soil N and subsoil P and LEAFK. Likewise, LEAFK decreased with increased NBDCT, BIO, and THAHOR and increased with increased PLDEN, thus indicating that a dilution of LEAFK occurred as better plant growth was promoted by higher levels of the three first variables. On the contrary, LEAFK accumulated as N and P became deficient with increased plant density.

The responses of LEAFK to the soil variables of THAHOR, DCMAX, SLOPE, DRAIN, CPL, and to the TILE and PPT15 variables demonstrated that the K availability, uptake, and leaf concentration were closely related to factors influencing the soil moisture conditions, particularly in the soil plow layer.

The SAMDIF variable had a quadratic effect on LEAFK which showed that maximum LEAFK occurred about 1 day before the silking date and that LEAFK was about 0.06% less if sampled 4 days before or after the date of maximum LEAFK. Weather factors did not affect this response as they did with LEAFN and LEAFP, probably because most of the K uptake occurred before leaf sampling time.

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ACKNOWLEDGMENTS

I wish to express my sincere appreciation and gratitude to Dr. Lloyd C. Dumenil for his guidance and advice throughout my graduate work at Iowa State University and for his invaluable assistance in the completion of this dissertation.

Thanks are also extended to Drs. I. C. Anderson, J. R. Webb, R. D. Voss, D. J. Nevins, and C. R. Stewart for serving on my graduate committee.

I am also grateful for the assistance of Mrs. Ina Couture in the typing of this dissertation.

Acknowledgment is given to the Rockefeller Foundation for its financial support that made my graduate studies possible.

This dissertation would not have been completed without the love, sacrifice, and understanding of my wife Amanda and sons Alejandro and Jose Alfonso, to whom it is dedicated with my deepest love and gratitude. Also, I wish to express my gratitude to my parents Francisca and Alfonso and to my sister Teresa for their love and encouragement.

APPENDIX

Table A1. Data listing for leaf nutrient concentrations, soil, weather, management, and other variables on tape FDCKAL, data set name ALLVAR, LABEL = (24,SL)

Columns	Variable	Columns	Variable	Columns	Variable
1-3	SAMDIF	81-82	MANURE	160-164	EXMO
4-6	SAMDATE	83-84	NROW	165-166	PAWC
7-11	LEAFN	85-86	PROW	167-168	NCODE1
12-16	LEAFP	87-88	KROW	169-170	NCODE2
17-21	LEAFK	89-91	NBDCT	171-172	PRECROP
22	Card no.	92-94	PBDCT	173-174	HYMAT
23-24	County	95-97	KBDCT	175-176	HYCROSS
25-26	Year	98-100	NTIME	177-179	TWP
27-28	Site	101-103	NSD	180-182	RANGE
29-31	YIELD	104-106	SDDATE	183-185	EROS
32-33	AREA	107-109	PMETH	186-188	THAHOR
34-36	TIME	110-112	KMETH	189-191	DRAIN
37-39	TREND	113-115	TILE	192-194	CPL
40-42	PLDEN	116-118	KCODE	195-197	CMAX
43-45	BARR	119-121	NRES1	198-200	DCMAX
46-48	RL3	122-124	PRES1	201	BIO
49-51	CRW	125-127	KRES1	202	LOESS/T
52-54	SL1	128-130	PRES2	203	TILL
55-57	CB1	131-133	KRES2	204	PALEO
58-60	CB2	134-136	PRES3	205	SAND
61-63	LEAFFEED	137-139	SLOPE	206	COLLUV
64-66	WEEDS	140-142	ROWSLP	207	ALLUV
67-68	CULT	143-145	PH1	208-210	PHMIN
69-70	PLOW	146-148	STN	211-213	DPHMIN
71-72	TILLAFT	149-151	STP1	214-216	DCAL
73-74	PLDATE	152-154	STK1	217-219	STP2
75-76	SLKDATE	155-159	DV	220-222	STK2
77-78	PLMETH				
79-80	ROWWID				

Table A2. Means and ranges of the weather indexes computed for the 75-day and 40-day periods before leaf sampling and for the two 20-day periods in the 40-day period before leaf sampling date

Variable[a]	Mean	Range	Variable[a]	Mean	Range
DT75	63.96	21.7-74.9	DTA	20.04	7.9-21.0
DX75	15.11	5.5-20.1	DXA	5.24	2.4-6.99
DW75	16.13	4.6-19.2	DWA	3.14	1.6-3.30
DV75	3.77	1.1-5.2	DVA	0.82	0.36-1.10
X175	2.79	0.7-3.9	X1A	0.49	0.21-0.66
PPT75	9.59	2.1-22.0	PPTA	3.04	0-11.6
PPT75W	2.40	0.4-5.7	PPTAW	0.48	0-1.94
DT40	38.11	15.9-41.0	DTB	18.07	4.5-20.0
DX40	9.70	4.6-12.3	DXB	4.45	1.0-6.5
DW40	8.66	3.4-9.4	DWB	5.52	1.4-6.1
DV40	2.18	0.9-2.9	DVB	1.35	0.3-2.0
X140	1.55	0.6-2.1	X1B	1.06	0.2-1.6
PPT40	5.87	0.1-16.8	PPTB	2.83	0.0-11.7
PPT40W	1.35	0.04-4.1	PPTBW	0.87	0.0-3.7
EXMO[b]	1.22	0-14.8			
PPT46[b]	6.74	0-19.6			

[a]Variables were described in Table 2.

[b]These were computed in the period of 3 to 49 days after planting.

Table A3. Means and ranges of the 5-day moisture stress and precipitation indexes and of the 8-day excess moisture and precipitation indexes

Variable[a]	Mean	Range	Variable	Mean	Range	Variable	Mean	Range
DT1	5.82	1.1-6.0	DX1	1.47	0.3-2.4	DW1	0.58	0.1-0.6
DT2	4.78	1.0-5.0	DX2	1.28	0.3-2.0	DW2	0.67	0.1-0.7
DT3	4.73	1.1-5.0	DX3	1.27	0.4-2.1	DW3	0.95	0.2-1.0
DT4	4.71	1.1-5.0	DX4	1.22	0.4-2.1	DW4	0.94	0.2-1.0
DT5	4.65	0.8-5.0	DX5	1.17	0.2-2.0	DW5	0.93	0.1-1.0
DT6	4.57	0.6-5.0	DX6	1.13	0.2-1.8	DW6	1.19	0.2-1.3
DT7	4.46	0.5-5.0	DX7	1.07	0.1-1.7	DW7	1.65	0.2-1.8
DT8	4.39	0.6-5.0	DX8	1.08	0.1-1.8	DW8	1.76	0.2-2.0
DV1	0.15	0.04-0.2	X11	0.07	0.02-0.1	PT1	0.77	0-8.3
DV2	0.18	0.04-0.3	X12	0.10	0.02-0.1	PT2	0.81	0-8.6
DV3	0.25	0.08-0.4	X13	0.15	0.05-0.2	PT3	0.83	0-6.2
DV4	0.24	0.07-0.4	X14	0.16	0.05-0.3	PT4	0.63	0-8.2
DV5	0.23	0.05-0.4	X15	0.17	0.04-0.3	PT5	0.71	0-7.9
DV6	0.29	0.04-0.5	X16	0.23	0.03-0.4	PT6	0.74	0-6.9
DV7	0.40	0.05-0.6	X17	0.32	0.04-0.5	PT7	0.71	0-7.7
DV8	0.43	0.06-0.7	X18	0.35	0.05-0.6	PT8	0.66	0-7.5
PT1W	0.08	0-0.8	EXM01	0.26	0-4.6	PTEM1	1.14	-[b]
PT2W	0.11	0-1.2	EXM02	0.28	0-6.0	PTEM2	1.21	-
PT3W	0.16	0-1.2	EXM03	0.23	0-5.4	PTEM3	1.25	-
PT4W	0.13	0-1.6	EXM04	0.19	0-5.0	PTEM4	1.23	-
PT5W	0.14	0-1.6	EXM05	0.14	0-3.8			
PT6W	0.19	0-2.1	EXM06	0.07	0-2.5			
PT7W	0.26	0-3.0						
PT8W	0.26	0-3.0						

[a]Variables are desceibed in Table 2.

[b]The ranges of these indexes were not computed.

Table A4. Means and ranges of the variables included in the LEAFN, LEAFP, and LEAFK regressions on soil and management variables

Variable[a]	Mean	Range	Variable	Mean	Range
LEAFN	2.89	1.43-3.68	KRES1	26.1	0-223
LEAFP	0.278	0.115-0.459	PRES2	13.5	0-88
LEAFK	2.08	0.61-3.30	PRES3	10.6	0-88
			NCODE1	23.2	8-40
SAMDATE[b]	28.1	7-51	KCODE	17.4	0-60
SLKDATE[b]	29.0	8-51			
SAMDIF	0.9	-6 to 8	PH1	15.3	1-32
			STN	63.3	24-119
BARR	4.9	0-53	STP1	32.7	5-222
RL3	8.3	0-99	STK1	225.8	35-928
CRW	15.0	10-52	PHMIN	18.0	4-37
SL1	4.2	0-84	STP2	18.0	5-98
CB1	3.3	0-38	STK2	52.7	14-294
CB2	13.7	0-99			
WEEDS	59.8	0-475	EROS	0.7	0-3
			THAHOR	33.7	0-61
CULT	2.8	0-7	PAWC	24.8	6-31
PLOW	0.7	0-2	DRAIN	42.4	10-85
TILLAFT	3.9	0-9	CPL	26.1	5-56
PLDEN	380.0	193-751	CMAX	31.9	4-60
PLDATE	23.5	0-54	DCMAX	53.7	15-127
PLMETH	0.4	0-1	BIO	4.6	1-5
ROWWID	28.5	0-48	SLOPE	4.3	0-20
ROWSLP	1.7	0-13			
HYMAT	3.1	1-5	LOESS/T	0.06	0-1
HYCROSS	1.7	1-4	TILL	0.25	0-1
			PALEO	0.03	0-1
MANURE	4.9	0-45	SAND	0.07	0-1
NROW	6.3	0-39	COLLUV	0.03	0-1
PROW	9.3	0-29	ALLUV	0.13	0-1
KROW	10.8	0-56			
NBDCT	68.4	0-280	DPHMIN	35.1	15-99
PBDCT	9.4	0-78	DCAL	30.1	0-137
KBDCT	12.2	0-149			
TILE	5.8	0-61	TWP	20.5	2-34
NRES1	42.3	0-336	RANGE	26.1	0-48
PRES1	12.6	0-88			

[a]Variables are described in Table 1.

[b]These variables were used to compute the SAMDIF variable and they were not included in the regression models.